DOT/FAA/RD-91/23

Research and Development Service
Washington, D.C. 20591

Tiltrotor Aircraft Noise - A Summary of the Presentations and Discussions At The 1991 FAA/Georgia Tech Workshop

K. K. Ahuja

Georgia Institute of Technology
Aerospace Laboratory, GTRI
Atlanta, Georgia 30332

Under Subcontract To:

Systems Control Technology, Inc.
1611 N. Kent Street, Suite 910
Arlington, VA 22209

January 1992

Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department
of Transportation

Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U. S. Department of Transportation in the interest of information exchnage. The United States Government assumes no liability for the contents or use thereof.

U.S. Department
of Transportation

**Federal Aviation
Administration**

800 Independence Ave., S.W.
Washington, D.C. 20591

NOV 19 1992

Dear Colleague:

Enclosed is **FAA/RD-91/23, TIltrotor Aircraft Noise - A Summary of the Presentations at the 1991 FAA/Georgia Tech Workshop.** This effort was initiated to help determine the requirements and priorities for future research and development related to new vertical flight technology such as the tiltrotor aircraft.

The final report was completed in January 1992, but due to unforseen delays in publishing, it has only recently been available for distribution. Even though the summary of this workshop was not available until now, the findings and recommendations from this two day session have helped the FAA to further define future actions in vertical flight noise research and development. The workshop had two objectives, (1) review the status of research and development in predicting and reducing tiltrotor noise, and (2) identify key technical and operational issues and the methods to address them.

Recent events with the military's V-22 Osprey Program and Congressional interest in civil tiltrotor operations have further highlighted the potential for this exciting new technology. Similarly, issues related to environmental impacts and noise are also being identified. The workshop that this report summarizes was an initial attempt at identifying the areas where critical research is required if future civil tiltrotor operations are to be compatible with the environment and gain public acceptance.

We welcome your recommendations and suggestions related to this area and other vertical flight noise abatement research and development needs. Please send them to:

Vertical Flight Program Office, ARD-30
Federal Aviation Administration
800 Independence Ave., S.W.
Washington, DC 20591

Gene S. Mead
Acting Manager, Vertical Flight Program Office

Enclosure

Technical Report Documentation Page

1. Report No. DOT/FAA/RD-91/23	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Tiltrotor Aircraft Noise - A Summary of the Presentations and Discussions at the 1991 FAA/Georgia Tech Workshop		5. Report Date January 1992 6. Performing Organization Code
7. Author (s) K.K. Ahuja/Georgia Tech Research Institute		8. Performing Organization Report No. A8924-1
9. Performing Organization Name and Address Systems Control Technology, Inc. 1611 North Kent Street, Suite 910 Arlington, VA 22209		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFA01-87-C-00014
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration 800 Independence Avenue, S.W. Washington, D.C. 20591		13. Type Report and Period Covered Final Report 14. Sponsoring Agency Code ARD-30

15. Supplementary Notes
ARD - 30 Vertical Flight Program Office

16. Abstract

Georgia Institute of Technology hosted a workshop in Atlanta on 28 and 29 March 1991 on the noise problems associated with tiltrotors. The workshop had two major objectives: (1) to review the status of research and development in predicting and reducing tiltrotor noise; and, (2) to identify key technical and operational issues and methods to address them. The second objective had both near term and far term implications. In the near term, the goal is to arrive at a level of technical credibility that can support decisions to develop urban and inner city markets. The long term goal is to target resources and actions which will lead to tiltrotor noise abatement and effective control.

The opening session of this workshop consisted of an overview and a discussion of the physics of tiltrotor noise mechanisms. A review of the available experimental data followed. A discourse on potential flight operational procedures to minimize noise impacts, and a general presentation of industry and government perspectives concluded the workshop.

Subsequent sessions were available ford participants to present observations on and experiences with the XV-15 and V-22. Operational experiences included flight tests, wind tunnel tests, and other simulations. Experiences with computational fluid dynamics codes, small-scale model testing, and other related research were shared.

This document provides a summary of the presentations and discussions that took place during the workshop.

17. Key Words Rotor Noise Helicopter Noise Tiltrotor Noise	Land Use Planning Tiltwing Noise BVI Noise Certification	18. Distribution Statement This document is available to the U.S. Public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 59	22. Price

Form DOT F 1700.7 (8-72) Reproduction of this document is authorized

TABLE OF CONTENTS

Section	Title	Page
1	INTRODUCTION	1
2	THE WORKSHOP AGENDA AND PARTICIPANTS	3
3	A SUMMARY OF THE PRESENTATIONS	7
3.1	Introduction Remarks	7
3.2	An Overview of FAA Activity	7
3.3	An Overview of NASA Headquarters Activity	8
3.4	A Tutorial on Tiltrotor Noise Mechanisms	11
3.5	Lessons Learned From Past Tiltrotor Noise Studies	12
3.6	An Overview of NASA Langley Activities	14
3.7	An Overview of NASA-AMES/U. S. Army Activities	15
3.8	An Overview of NASA LEWIS Activities	20
3.9	Tiltrotor Noise Prediction Methodologies	20
3.10	Tiltrotor Flight Testing	21
3.11	Tiltrotor Design and Operational Considerations	24
3.12	Proper Land Use Planning and Public Acceptance	28
3.13	Rotorcraft Flow Diagnostics	31
3.14	A Wish List of R&D Programs in Tiltrotor Aeroacoustics	31
3.15	Panel Discussion	35
4	SUMMARY OF DISCUSSIONS DURING QUESTION AND ANSWER PERIOD	36
4.1	FAA and Certification Issues	36
4.2	Simulation Issues	36
4.3	Noise Standards for the Military	37
4.4	Low-Frequency Noise of Tiltrotor Aircraft and Noise Metrics	37
4.5	What Decibel Level Will Be Acceptable?	37
4.6	Tiltwing Versus Tiltrotor	38
4.7	Model-Scale Experiments	38
4.8	Availability of Funds For R & D	38
4.9	En Route Noise	38
4.10	V-22 Noise Data	38
4.11	Quality of Data Acquired Statically	39
4.12	Noise Reduction	39
4.13	Validation Tests	39
5	PANEL DISCUSSION	40
5.1	Funding	40
5.2	Second Generation V-22	40
5.3	Interagency Cooperation	40
5.4	Noise Reduction	40
5.5	Is There A Civil Tiltrotor Market?	41

TABLE OF CONTENTS (Cont.)

Section	Title	Page
5.6	Tiltwing Versus Tiltrotor	43
5.7	Other Issues	44
5.8	Noise Prediction	44
5.9	The Biggest Challenge is BVI	44
5.10	Design for Noise Capability	45
5.11	Future Work	45
6	SUMMARY AND RECOMMENDATIONS	46
6.1	Noise Generation	46
6.2	Noise Propagation	46
6.3	Noise Detection (Certification)	46
6.4	Noise Prediction	47
6.5	Noise Reduction	47
6.6	Tiltrotor Versus Tiltwing	47
6.7	Certification Procedures	47
6.8	Simulations	48
6.9	Small-Scale Models	48
6.10	Design for Noise Capability	48
6.11	Tiltrotor Market, Infrastructure, and Acoustics	48
6.12	Land Use Planning and Public Acceptance	48
6.13	Interaction With The Academic Community	49
6.14	Lessons From Propfan Research	49
6.15	Other Issues	49
6.16	Second Workshop on Tiltrotor Aircraft Noise	49
	APPENDIX 1 Workshop Participants	51
	APPENDIX 2 Acronyms	58

SECTION 1
INTRODUCTION

The speed, range, and fuel economy of the tiltrotor aircraft make it a suitable candidate for short-to-medium range (100 to 500 NM) commercial or executive transport applications. Tiltrotor aircraft are expected to become a significant part of the civil rotorcraft market within the next 15 years. Vertiports, which are heliports that can accommodate commercial tiltrotors, will need to be planned for urban areas to maximize the efficiency of vertical flight technology. One of the important issues that will be addressed by regulatory agencies and industry is tiltrotor noise and its impacts on the community, the passengers and air crew, and the airframe structure. Impact on the community will be a particularly important issue since community acceptance is essential to the successful development and operation of passenger carrying tiltrotors.

Under the sponsorship of FAA, the Georgia Institute of Technology hosted a workshop on the tiltrotor noise issues on 28 and 29 March 1991. The workshop was organized by Dr. Krish Ahuja, Head of the Acoustics Branch of Aerospace Sciences Laboratory of the Georgia Tech Research Institute and and a Professor in the School of Aerospace Engineering at Georgia Tech.

The workshop had two major objectives: (1) to review the status of research and development in predicting and reducing tiltrotor noise; and, (2) to identify key technical and operational issues. The second objective had both near term and far term implications. In the near term, the goal is to arrive at a level of technical credibility that can support decisions to develop urban and inner city markets. The long term goal is to target resources and actions which will lead to tiltrotor noise abatement and effective control.

The opening session of this workshop consisted of an overview and a discussion of the physics of tiltrotor noise mechanisms. A review of the available experimental data followed. A discourse on the potential flight operational procedures to minimize noise impacts, and a general presentation of industry and government perspectives concluded the workshop.

Subsequent sessions were available for participants to present observations on and experiences with the XV-15 and V-22. Operational experiences include flight tests, wind tunnel tests, and other simulations. Experiences with computational fluid dynamics codes, small-scale model testing, and other related research were shared.

This document provides a summary of the presentations and discussions that took place during the workshop. The report also includes the highlights of the discussions, the actions recommended, and where possible, the parties responsible for various actions.

SECTION 2
THE WORKSHOP AGENDA AND PARTICIPANTS

The agenda of the workshop is shown in the following pages. A list of participants of the workshop is attached as Appendix 1.

Workshop Agenda

Thursday, March 28

WELCOME - DR. D. GRACE,
Vice President and Director: Georgia Tech Research Institute, Atlanta, GA

INTRODUCTORY REMARKS - DR. K.
K. AHUJA, Head, Acoustics Branch & Prof. of Aerospace Eng.
Georgia Institute of Technology, Atlanta, GA

Overview of ARD-30
JIM MCDANIEL, Director, Vertical Flight Special Program Office
FAA Headquarters, Washington, DC

FAA Aircraft Noise Overview
STEVE FISHER, Project Manager, Vertical Flight Special Program Office
FAA Headquarters, Washington, DC

NASA Rotorcraft Program Overview
MAJOR PAUL W. LOSIER, USA
Rotorcraft Program Mgr., Aeronautics Directorate
NASA Headquarters, Washington, DC

Break

Advanced Tiltrotor Transport Market and Technology Issues
GEORGE UNGER, Manager, Vehicle Aerodynamics
NASA Headquarters, Washington, DC

Lunch

Tiltrotor Noise Mechanisms and Predictions
PROFESSOR ALBERT R. GEORGE
Cornell University, Ithaca, NY

Tiltrotor Noise Reduction Studies Some Reflections and Guidance From the Past
DR. FREDRIC H. SCHMITZ, Chief, Full-Scale Aerodynamics Research Division
NASA-Ames Research Center, Moffett Field, CA

Overview of NASA/LaRC Acoustics Research Program
DR. JAMES C. YU, Asst. Chief, Acoustics Division & Manager, Rotorcraft R & T Office
NASA-Langley Research Center, Hampton, VA

Overview of NASA High-Speed Rotorcraft Studies
WILLIAM J. SNYDER, Chief , Rotor Technology Branch,
NASA-Ames Research Center, Moffett Field, CA

Tiltrotor Acoustic Research at NFAC
DR. MARIANNE MOSHER, Aerospace Engineer
NASA-Ames Research Center, Moffett Field, CA

Break

Tiltrotor Aeroacoustics Activity at AFDD
DR. YUNG H. YU, Chief, Fluid Mechanics Division
Aeroflightdynamics Directorate (AFDD)
NASA-Ames Research Center, Moffett Field, CA

NASA/Army Tiltrotor Aeroacoustic Model Program
LARRY YOUNG, Project Director, Rotorcraft Aeromechanics Branch
NASA-Ames Research Center,
Moffett Field, CA

Aeroacoustic Lessons Learned From the Advanced Turboprop Program
JOHN F. GROENEWEG, Chief, Propeller & Acoustics Tech. Branch
NASA-Lewis Research Center,
Cleveland, OH

Theoretical Prediction of Propeller Noise
NIGEL PEAKE, Research Fellow
Department of Applied Mathematics and Theoretical Physics
University of Cambridge,
Cambridge, U. K.

Tiltrotor Noise Prediction Development
MR. ROBERT GOLUB, Manager, Noise Prediction Technology, Aeroacoustics Branch
NASA-Langley Research Center, Hampton, VA

Friday, March 29

Flight Test Programs at the Langley Research Center
DAVID A CONNER & KEN RUTLEDGE
Research Engineers, Acoustics Division
NASA-Langley Research Center, Hampton, VA

Tiltrotor Flight Test Experience & Advanced Blade Development
DR. M. D. MAISEL
Chief, Flight Experiment Branch
NASA-Ames Research Center, Moffett Field, CA

Development and Testing of XV-15
CLIFFORD MCKEITHAN, School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, Ga.

Design & Operational Noise Issues in the Future of Commercial Tiltrotors
HARRY STERNFELD, JR., Manager, Noise Technology & HARRY ALEXANDER
Boeing Defense and Space Group, Philadelphia, PA

Break

Preliminary Design & Operational Considerations
CHARLIE COX, Chief Acoustics Engineer
Bell Helicopter Textron, Fort Worth, TX

Tiltrotor Aircraft Technology, Where it Should Go
CHARLIE CRAWFORD, Head, Systems Development Branch
Georgia Tech Research Institute, Atlanta, GA

Three Dimensional Planning and Noise Control
DR. CLIFFORD D. BRAGDON, Special Asst., Office of the Pres., Prof. of City Planning
Georgia Institute of Technology, Atlanta, GA

Lunch

Urban Compatibility: A Model Ordinance
DEBORAH PEISEN, Systems Analyst
Systems Control Technology, Inc., Arlington, VA

What Will The Neighbors Think?
RON REBER, Manager, Commercial Tiltrotor Program
Bell Helicopter Textron, Fort Worth, TX

Rotorcraft Flowfield Diagnostics
DR. NARAYANAN M. KOMERATH, Associate Professor, School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA

A Typical Program for Tiltrotor Aircraft Aeroacoustics Research and Development
DR. K. K. AHUJA, Head, Acoustics Branch & Professor of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA

Break

Panel Discussion

SECTION 3
A SUMMARY OF THE PRESENTATIONS

3.1 INTRODUCTORY REMARKS

In his introductory remarks, **Dr. Krish Ahuja** of Georgia Institute of Technology used very low frequency loudspeakers to demonstrate low frequency noise. At frequencies in the range of 20 to 40 Hz at very moderate noise levels, the ceiling of the auditorium started to shake. The same speaker was then used to play pre-recorded noise levels from XV-15 and V-22 aircraft, provided by Mr. David Conner of NASA Langley Research Center. The noise from tiltrotor aircraft may well dominate the low frequency portion of the noise spectrum and may be crucial to the success of a civil tiltrotor aircraft. The key message of the introductory talk was that it is a must that we know as soon as possible what are acceptable noise levels from tiltrotor aircraft.

3.2 AN OVERVIEW OF FAA ACTIVITY

Mr. Jim McDaniel, Director of the Vertical Flight Program Office at FAA Headquarters, provided an overview of the vertical flight research and development program. He provided an overview of the Vertical Flight Program Office and its mission. This mission includes planning and implementation of those actions necessary for the introduction of conventional rotorcraft, tiltrotor, and other emerging powered lift aircraft into the National Airspace System (NAS). The Vertical Flight Program Office conducts studies and efforts to develop and evaluate procedures, systems, and techniques which will enable safer and more effective use of vertical flight aircraft. This office is a national focal point for vertical flight programs at the FAA and promotes vertical flight technology.

Mr. **Steve Fisher**, a project manager in the Vertical Flight Program Office (VFPO) provided an overview of the FAA Tiltrotor aircraft noise R & D program. He described the interactions between the Vertical Flight Program Office (ARD-30) and the Office of Environment and Energy (AEE-100). In relation to tiltrotor aircraft noise, ARD-30 is concerned with tiltrotor noise influence on the National Airspace System, its impact on design and flight operations, and its role in terminal procedures. The Office of Environment and Energy (AEE-100) is responsible for

determining the technology for noise abatement as required by the 1972 Noise Control Act. This office also determines the noise levels needed to support the environmental impact assessment. It is the responsibility of this office to deal with matters pertaining to aircraft noise certification. Mr. Fisher stressed that all scenarios of noise R & D planning must incorporate all aspects of tiltrotor aircraft flight dynamics, such as airplane, helicopter, and conversion modes, steep angle approaches, new or unique noise characteristics, noise footprint arcs reflecting circular approaches and impacts from operating in close proximity to residential and urban areas. He also stressed the need for all interested parties to have access to the results of the FAA R & D program. These parties include federal agencies, state agencies, municipalities, associations, institutions, manufacturers, and the general public. Mr. Fisher also talked about the Rotorcraft Master Plan (RMP). This plan includes inputs from various elements in the FAA.

3.3 AN OVERVIEW OF NASA HEADQUARTERS ACTIVITY

Major **Paul Losier**, USA, Rotorcraft Program Manager - Aeronautics Directorate at NASA Headquarters, provided an overview of the rotorcraft technology program at NASA. He showed a diagram of funds expended for military rotorcraft and those for civil rotorcraft in the years 1982 through 1990. It portrayed a bleak picture of how the spending for military rotorcraft had increased significantly since 1987, while the trend for the civil rotorcraft was just the opposite. Major Losier described the commitments of the NASA Office of Aeronautics Exploration and Technology (OAET). It is committed to position U. S. industry for continued aerospace leadership into the 21st century. He alluded to five specific aeronautics strategic thrusts, two of which are applicable to the subject of the workshop. They deal with : (1) subsonic aircraft/national airspace and (2) high-performance military aircraft. Each of these thrusts has a number of key objectives. The relevant objectives corresponding to these two thrusts are:

1. Developing critical technologies for safe, economical and environmentally acceptable operation of rotorcraft in the national airspace system.

2. Developing critical technologies for rotorcraft capable of high speed, automated nap-of-the earth flight and 50 % greater agility.

All aspects of acoustics, in particular noise control concepts, are key elements to meeting the objectives.

Major Losier indicated that a commercial tiltrotor was indeed feasible and economically competitive. Envisioning the scenario for year 2010, he listed problems caused by congestion, increased environmental concern, increased traffic control complexity, limited airport expansion, increased travel, increased need for helicopter emergency medical service (EMS) and disaster response. Further, the expansion of industrial operations into rural areas compounds transportation needs. He stressed the usefulness of a commercial tiltrotor aircraft in supporting these needs. Among various attributes the commercial tiltrotor must display, reduced noise was at the top of the list.

Mr. **George Unger**, Manager of Vehicle Dynamics at NASA Headquarters, provided an overview of the advanced tiltrotor aircraft market and discussed the technology issues. He discussed civil tiltrotor missions and applications, technological benefits, and projected total operating costs. He provided a very succinct description of the market analysis studies for tiltrotor aircraft.

Mr. Unger stressed the need for a "market responsive design." Such a design uses few V-22 military components. It will have a market in excess of 2600 medium tiltrotor aircraft with a $6-7 billion in revenue per year. It will grow by the year 2000 to encompass all sizes. Civil tiltrotor thus has a large market and is the only passenger-carrying market large enough to amortize initial investment (with a minimum of 330 aircraft produced at affordable rates). Tiltrotor aircraft operating costs will be higher than those for the fixed wing alternatives in this market and must be offset by sites convenient to demand areas or must be subsidized by regional agencies to support regional goals and economic growth.

It was recommended that NASA should continue providing support for a market responsive design and FAA should develop standards for early introduction. A flight demonstration/validation plan should also be developed under a partnership concept.

Mr. Unger also talked about the research priorities applicable to "barrier" issues, design base technologies, and enhancing technologies. Some of the noise issues under these research priorities are external noise levels in approach, steep approach criteria, 4-bladed rotor design, interior noise, and active control of noise, vibration, stability, and aeroelasticity.

Unger named four ***key technology goals*** for civil tiltrotor aircraft:

1. Residential vertiport operation should not exceed 65 Ldn for 50 flights/day within 50 acres of exposure.
2. Steep approach IFR certification should include level 1 handling qualities to 15 degrees and should ensure single engine failure safety.
3. Tiltrotor aircraft should provide passenger comfort associated with airplanes and cabin noise level less than 78 dBA and vibration levels less than 0.03 g's in cruise flight.
4. Tiltrotor portal-to-portal cost should be similar to that of a fixed wing alternative and have a gross weight less than 1000 lbs per passenger. It should have a price less than $350,000, and a cruise lift to drag ratio (L/D) of greater than 12.

Referring to the civil tiltrotor technology goals, Mr. Unger listed noise reduction as a major challenge for the marketability of the civil tiltrotor. He outlined the noise benefits of advanced technology blades and the need for increasing the number of blades and reducing the tip speed to reduce noise from tiltrotor aircraft.

Mr. Unger also provided an extensive list of near term (2-4 years) and long term (4-8 years) goals for tiltrotor noise research and technology. The ***highest priority*** listed was reducing blade vortex interaction (BVI) generated noise.

The tasks defined by Mr. Unger were as follows:

Near Term Tasks:

1. Conduct detailed noise surveys of V-22 and XV-15/ATB flights in approach with matrix of speeds & descent angles.
2. Conduct tip shape prediction & experiments on ATB blades.
3. Develop pressure-tapped blade data in high acoustic quality wind tunnels.
4. Conduct simulated aircraft noise abatement maneuvers using cuing and displays for proper noise minimization.
5. Validate the research code for BVI prediction.

Long Term Tasks:

1. Assess the potential of 4+ bladed rotors for noise reduction.
2. Assess the active rotor control for noise reduction.
3. Provide a production code for BVI prediction.
4. Assess innovative devices for noise control
   - active tip devices

- variable diameter.

The following areas of ***university involvement*** were included in Mr. Unger's concluding comments.

Universities could:

1. Use the existing data bases to understand noise sources and predict them.
2. Predict tip vortex size, strength, and dissipation from the first principles.
3. Evaluate and establish retreating blade noise sources.
4. Develop innovative solutions to:
   - low speed velocity measurement
   - display of exterior noise to pilot
   - structural control of interior noise.
5. Participate in NASA research.

3.4 A TUTORIAL ON TILTROTOR NOISE MECHANISMS

Professor **Al George** of Cornell University gave a tutorial on tiltrotor noise mechanisms and predictions. He also showed a helium bubble flow visualization of fountain effects using an experimental setup in his laboratory. He pointed out that the key differences in noise of tiltrotor aircraft compared to a helicopter stem from the differences in the associated aerodynamics. These differences are associated with :

1. *Wing effects:* Since a helicopter does not have a wing, the tiltrotor combined with a wing has unique features associated with ground plane, fountain, and stall/separation effects.

2. *Induced velocity effects:* Induced velocity associated with tiltrotor aircraft can affect the blade-vortex interaction.

3. *Other:* Other effects include rotor spacing and phasing, which can affect low frequency noise and noise directivity; near field of tips on fuselage, which can affect cabin noise; and other rotor/airframe interactions.

The ***lessons*** from Professor George's talk can be summarized as follows:

1. Current aerodynamic understanding and characterization of highly unsteady and turbulent flow fields associated with hover are insufficient to determine definitive noise impacts.

2. Better prediction capability is needed for wakes and BVI aerodynamics analysis.
3. Most but not all noise mechanisms are understood physically.
4. Given the aerodynamics, accurate prediction methods are available for discrete frequency and impulsive noise mechanisms. Prediction methods for broadband noise, however, need further improvement.
5. Work towards predicting noise from highly unsteady turbulent flows interacting with rotors needs to be done.

Some of the ***research priorities*** in the area of tiltrotor aircraft noise are summarized below:

1. Characterize and control fountain flow phenomena through flow and acoustic experiments and acoustic analysis. Also examine ground effects of this phenomena.
2. Perform calculation of BVI for various tilt angle/descent/speed operating conditions and relate these to noise footprints impacts.
3. Measure noise signature and spectra for a wide range of precisely determined tiltrotor operating conditions.
4. Develop improved broadband noise predictions near the rotor plane.
5. Develop a capability for free-wake calculation for tiltrotor aircraft for a wide range of operating conditions.
6. Improve the BVI aerodynamics and aeroacoustic analyses for given wake and blade geometries.

3.5 LESSONS LEARNED FROM PAST TILTROTOR NOISE STUDIES

Dr. **Fredric Schmitz,** Chief of the Full-Scale Aerodyanamics Research Division at NASA-Ames Research Center, provided his reflections on lessons learned from past tiltrotor noise reduction studies. Schmitz pointed out that, assuming that perceived noise level (PNL) and effective PNL (EPNL) are adequate measures of tiltrotor annoyance, the three most important factors that can be used to mitigate external noise are: (1) tiltrotor design, (2) flight trajectory management and vehicle configuration control, and (3) tiltrotor terminal site selection. Dr. Schmitz then alluded to a number of earlier studies since 1972 on noise mitigation. He then discussed the design characteristics of Vertol 160 tiltrotor aircraft and discussed various tiltrotor acoustic performance models in existence applicable to tiltrotor aircraft noise. Dr. Schmitz presented a number of noise footprints as PNL comparison between maximum performance takeoff and other modes of takeoff (helicopter, conventional takeoff, landing, vertical ascent, extended vertical ascent). He also provided an acoustic annoyance profile of Palo Alto and San Carlos as a function of current technology and

future technology. These profiles were presented in the form of reactions of people to noise versus number of people. The reactions included no reaction, sporadic complaints, widespread complaints, threat of legal action, and vigorous action.

Using trends derived from Boeing Vertol Whirl and other large-scale data and validation of tiltrotor computer model trends using hover data, Dr. Schmitz listed the following parameters as the key design parameters influencing rotor noise: (1) tip speed, (2) thrust, (3) number of blades, (4) blade tip shape, (5) blade planform, (6) airfoil section, and (7) blade twist. He also provided a design comparison of quiet and standard tiltrotor aircraft in terms of characteristics, performance, weight and noise. The ***major conclusions*** drawn by Dr. Schmitz from early work are listed below:

1. The most subjectively annoying tiltrotor noise is caused by BVI. It sets the level of PNL in many terminal area operations.
2. Some reduction of PNL is possible through blade tip planform changes.
3. Flight trajectory management can be effectively used to mitigate PNLs in noise sensitive areas near vertiports sites.
4. Land use near a vertiport will determine the optimum (minimum) noise abatement profile.
5. The most effective way to control overall sound pressure levels (OASPL) and PNL is to control : (a) tip speed and (b) disk loading. The number of blades plays a smaller role in controlling PNLs but is important in controlling OASPL.
6. 5-10 dB PNL reductions are achievable with some performance sacrifices, but 10-20 dB PNL reductions are very difficult and will require major investment in basic noise reduction technology, new noise reduction concepts, and/or new vertical take-off and landing (VTOL) concepts. Likewise, 5-10 dB reductions in OASPL are achievable with minor performance sacrifices, but 10-20 dB reductions in OASPL will be difficult but will probably be achievable with significant performance sacrifices.

The ***recommendations*** made by Dr. Schmitz are summarized below.

1. Establish a level of tiltrotor noise reduction required for acceptable operation at specified classes of vertiports.
2. Undertake a further market analysis to evaluate the use of tiltrotor aircraft at these selected vertiports subject to realistic commercial acoustic and performance constraints.
3. Divide the civilian noise reduction efforts into two research foci: a near term focus and a long term focus. The near term focus should aim for 5-10 dB PNL reduction through extrapolations

of existing methods and technologies. The long term focus, on the other hand, should aim at reducing PNLs by 10-20 dB through development of innovative technologies.

4. Validate noise reduction technologies using high fidelity experiments where it is possible to confidently isolate particular noise reduction methods and techniques.
5. Focus emphasis on reducing tiltrotor noise BVI since BVI noise sets the level of annoyance of tiltrotors.

3.6 AN OVERVIEW OF NASA LANGLEY ACTIVITIES

Dr. **James C. Yu**, Assistant chief of the Acoustics Division at NASA Langley Research Center, provided an overview of NASA Langley's rotorcraft acoustics research program. Langley's rotorcraft program is focused on both civil and military needs and has the goal of developing and validating innovative technology for cost-effective design of highly efficient, low noise and vibration aircraft. Dr. Yu described the objectives and recent accomplishments under the following five areas of the rotorcraft acoustics program: (1) fundamental analysis and knowledge base, (2) system noise prediction and validation, (3) design-for-noise methodology, (4) innovative noise reduction concepts, and (5) interior noise control. Dr. Yu also provided some background on Langley developed prediction codes, which were later covered in more detail by Mr. Robert Golub, also of NASA-Langley. He also talked about the NASA/Army tiltrotor aeroacoustics model (TRAM) that will provide an advanced technology testbed for next generation quiet and highly efficient tiltrotor systems. This is a large size model (approx. 25% full scale) for scaling fidelity, has a fully instrumented blade, and can be configured for isolated rotor, semi-span model, or a full-span model. It is likely to prove to be a national resource for a coordinated effort. It is slated for a broad range of testing in the Duits-Nederlandse Wind Tunnel (DNW), 40 x 80 wind tunnel, Transonic Dynamics Tunnel (TDT), and 14 X 22 wind tunnel in FY 93-95.

Dr. Yu also presented selected ground noise contours generated from XV-15 tiltrotor far-field acoustics flight tests. He also alluded to NASA/Navy V-22 tiltrotor far-field acoustic tests. Dr. Yu referred to design-for-noise methodology development. The key objective here is to develop an integrated rotorcraft design and optimization methodology including performance, aerodynamics, dynamics and acoustics and to provide a methodology for systematic acoustic tradeoffs for low noise rotorcraft development. This is a new approach that calls for optimum integration of a number of technologies. Current efforts are aimed at acoustic design tradeoffs for the XV-15 and for integrated rotor design and optimization through combined acoustic/performance optimization. Such combined acoustic/performance optimization is accomplished through a judicious combination of appropriate noise prediction codes (such as WOPWOP) and performance,

aerodynamics and dynamics prediction codes (such as CAMRAD/JA). Appropriate account is taken of all the design variables, such as blade planform, tip speed, rotor radius, and number of blades. Additional constraints are imposed by the acoustics, such as no shocks allowed on the blades, or no blade-vortex interaction allowed. These constraints can be removed as the prediction technology becomes available to predict high speed interaction (HSI) and BVI noise. He discussed ongoing programs on innovative rotorcraft noise reduction concepts. Three concepts mentioned relate to vortex alleviation, active flap control, and double-swept tip; however, no results on these concepts were presented. Dr. Yu described the active control effort ongoing at NASA Langley to control interior noise.

Technology thrusts at NASA Langley for the future are as follows:

1. Correlation of airloads and BVI.
2. Analytical prediction of BVI and shock noise.
3. System Noise prediction and validation for advanced aircraft.
4. Comprehensive knowledge base for tiltrotor noise.
5. Design-for-noise methodology for rotorcraft.
6. Validation of innovative noise concepts.
7. Validation of advanced active interior noise control concepts.
8. Synergistic cooperations with NASA Ames, FAA, Department of Defense , industry and academia.

3.7 AN OVERVIEW OF NASA-AMES/U. S. ARMY ACTIVITIES

Dr. **John Zuk** of NASA Ames Research Center provided an overview of NASA Ames high speed rotorcraft activities on behalf of **William J. Snyder**, rotorcraft coordinator and chief of Rotorcraft Technology Branch at NASA Ames. The acoustics activities at NASA Ames run in close cooperation with NASA Langley and the U. S. Army. Dr. Zuk focused on future directions. He alluded to a high speed rotorcraft contracted study, the result of which was the selection of candidate high-speed rotorcraft. Out of a total of 20 potential concepts, preliminary designs of rotorcraft with five concepts were proposed. These were: (1) conventional tiltrotor, (2) canard tiltrotor, (3) folding tiltrotor, (4) variable diameter tiltrotor, and (5) tilt wing. Out of these five designs, two were selected as the prime candidates for future development. These were: the folding tiltrotor (FTR) and the canard tiltrotor (CTR). The latter is to be equipped with swept blades. Dr. Zuk then gave a list of key areas of technology investment along with a very comprehensive and useful block diagram on what it will take to start from the existing research

and technology base and accomplish the final technology base for advanced tiltrotor transport. Establishment of advanced civil tiltrotor requirements, definition of quiet, high speed rotors, civil tiltrotor simulation to explore steep approach limits, model-scale testing, large-scale testing in wind tunnels, and flight demonstrations were some of the key elements to establish the technology base for advanced tiltrotor transport.

Dr. Zuk pointed out that tiltrotors are considered to be the mainline configuration for NASA Ames future high speed rotorcraft activity. Alternative configurations, specifically tiltwings and variable diameter tiltrotors will also be investigated as they offer certain advantages. Dr. Zuk's overview is summarized as follows:

1. The tiltrotor and/or related vehicles appear to be leading candidates for alleviating the transportation congestion problem of the nation.
2. Noise is a barrier issue for advanced rotorcraft in this role, but low noise without productivity gains is a losing proposition. Economics is still king!
3. Introductory passenger service with tiltrotors must rely on operational control of noise, i.e., operating in non-sensitive areas and using design parameters such as tip speed.
4. Full exploitation of advanced rotorcraft in passenger service will be the payoff of extensive research that provides the technology base for low noise, high speed (productivity) configurations.

Dr. Zuk also presented a number of wish lists in the form of ultimate "deliverables and payoff" future research programs to develop a matured advanced tiltrotor transport technology. These ***wish lists*** are summarized below:

1. High quality tiltrotor airloads data base.
2. Improved comprehensive computational fluid dynamics (CFD) analysis methods for tiltrotor transport rotors.
3. Tools for designing low-noise, high speed tiltrotor transport rotors.
4. Validated analytical methods and technologies which pay off in low noise and high performance tiltrotor transport designs early in the next century and support U.S. leadership in tiltrotor technology.
5. Defined noise footprints and airspace requirements for vertiport design.
6. Validated flight and air traffic control procedures to minimize noise and maximize efficiency.
7. Validated control/display concepts for precision control and acceptable pilot workload.

8. Civil tiltrotor cockpit design and crew training guidelines.
9. Validated technology base for low noise, high speed tiltrotor transport rotor designs.

Dr. **Marianne Mosher** of the Rotorcraft Aeromechanics Branch at NASA Ames Research Center provided an overview of past, current, and future rotor research at the National Full-Scale Aerodynamics Complex (NFAC) facilities. These facilities consist of 40 by 80, 80 by 120, and 7 by 10 foot wind tunnels; an outdoor aerodynamic facility (OARF); and the computational facilities at Ames consisting of CRAY Y-MP, CRAY 2, and a number of workstations. Dr. Mosher briefly described past research on tiltrotors, which involved: (1) the XV-3 , (2) Boeing and Bell rotor/wing stability tests, (3) XV-15 propeller performance testing, (4) XV-15 aircraft testing in a 40 by 80 foot wind tunnel, (5) a JVX hover evaluation at OARF, (6) a tiltrotor wake study, (7) a V-22 download alleviation study, and (8) a model-scale hover study. Dr. Mosher then presented selected data from these studies.

Current research at NFAC includes rotor/wing tests in a 40 by 80 foot wind tunnel, in-flight rotorcraft acoustics program, and aerodynamic modeling of tiltrotors with computers. Current testing involves rotors associated with V-22, advanced technology blades (ATB), and XV-15. Testing of V-22 rotors with wing is also part of the current plans. These tests are being conducted for tip Mach numbers of 0.575 and 0.625, and tunnel Mach numbers of 0.15, 0.20, 0.25, and 0.30. The in-flight rotorcraft acoustics program (IRAP) includes flight tests with helicopters and tiltrotors with rotor systems identical to those tested in NFAC, correlation of computational and experimental data, and wind tunnel and flight noise data.

The ***current tiltrotor computational research*** at NFAC is directed at :

1. Prediction of tiltrotor performance and loads through CAMRAD/JA and EHPIC codes.
2 Analyses for prediction and reduction of rotor/wing downloads through Panel methods and finite difference methods.
3 BVI modeling.

Of particular note is the ***future planned tiltrotor research*** by the Rotorcraft Aeromechanics Branch at NASA Ames. It consists of the following six objectives:

1. Document V-22, XV-15, and ATB rotor noise in on-going 40 x 80 foot tunnel test program.
    - Near field noise comparison for each rotor
    - V-22 noise with and without wing

2. Perform small-scale V-22 rotor/wing acoustics experiment in hover.
   - Isolated rotor
   - Rotor/wing design sensitivities to noise

3. Acquire XV-15 aircraft noise in-flight with YO-3A aircraft under in-flight rotorcraft acoustics program (IRAP).
   - Quantify BVI noise in approach
   - Provide insight into scaling laws
   - Determine low noise flight profiles

4. Assess noise field for tiltrotors in transition flight in 80 x 120 ft. tunnel test using large-scale V-22 and XV-15 metal rotors.
   - Rotor in transition flight with and without rotors
   - Determine low noise flight profiles

5. Pursue development of CFD models for airloads and noise prediction and identify noise reduction designs and operating procedures.

6. Investigate unique tiltrotor noise sources in full-span with tiltrotor aeroacoustic model and validate computational acoustics models.

Dr. **Yung Yu**, chief of the Fluid Dynamics Division at U. S. Army's Aero Flight Dynamics Directorate (AFDD), AVSCOM, located at Ames Research center, provided an overview of tiltrotor aeroacoustic activities at AFDD.

The U. S. Army is the lead service for DoD rotorcraft R&D programs. Its rotorcraft research focus is on highly maneuverable, low observable technology, which is driven by military mission requirements as well as by fly-neighborly concepts. The military mission requirements include deep penetration and clandestine operations, and as such, low noise signatures are very important. Similarly, fly-neighborly concepts include training pilots and modifying flight operations in populated areas for reduced impacts on community noise. **Dr. Yu stressed the need for developing and validating comprehensive CFD codes for tiltrotor configurations.** Noise has been pointed out to be an important issue in each of the three flight regimes , namely, hover, conversion, and cruise. Other important issues are download reduction in hover, vibrations

and stability during conversion, and drag divergence, prop-wash, airframe aerodynamics, transonic effects and loads during cruise. Dr. Yu presented selected comparisons between measured and calculated results, and stressed a need for better turbulence modeling. He also outlined the future plans for tests in DNW. The first phase of testing, which involved a Boeing helicopter (360), MDHC helicopter (Harp), and a Sikorsky/UTRC aircraft (UH-60A, Berp Tip), has been completed.

In the second phase (FY 91 - FY 94), higher harmonic control (HHC) tests with B0-105 pressure blades are scheduled for 1993 and a tiltrotor model will be tested in 1994. Dr. Yu also mentioned the existence of excellent cooperation between industry, NASA, and the Army. He concluded his presentation emphasizing a need for innovative, high risk ideas to reduce the noise and vibration of tiltrotor aircraft.

Mr. **Larry Young**, project director of the NASA/Army tiltrotor aeroacoustic program (TRAM) and group leader of high speed rotorcraft and tiltrotor technology at NASA Ames Research Center, provided an account of the TRAM program. A 1/4 scale V-22 tiltrotor aircraft model is to be developed for technology development and evaluation. The model will be configured for testing as an isolated rotor, semi-span rotor/wing, and as a full-span model. NASA Ames, NASA Langley, and the U. S. Army AFDD are the participating research organizations in the TRAM program. Aeroacoustic tests are planned in several NASA and European wind tunnels in FY 93 through FY 1995.

The TRAM initial configuration is designed to accommodate acoustic and performance testing. It will be equipped with two rotor balances. A sting balance will be used with the full-span TRAM, and tunnel scales will be used with the semispan TRAM. The right-hand rotor will be instrumented with 100 to 200 pressure transducers. There are no plans to mount pressure transducers on the fuselage/wing surfaces. All wing/empannage control surfaces and nacelle tilt will be ground adjustable. Only the rotors will be scaled dynamically; the wing/nacelles will be structurally stiff to insure dynamic stability. Building this comprehensive model is an ambitious goal, but the results generated from its planned testing will certainly establish "design for noise" capability for next generation tiltrotor aircraft and help develop and demonstrate quiet and fuel efficient tiltrotor systems.

3.8 AN OVERVIEW OF NASA LEWIS ACTIVITIES

Dr. **John Groeneweg,** chief of the Propeller and Acoustics Technology Branch at NASA Lewis Research Center, provided the benefit of his experience in the area of turboprops and turbofans noise. He presented a brief summary of the advanced turboprop program at NASA Lewis and compared the structural and operational aspects of turboprops and tiltrotors. He outlined the research issues and programs on advanced turboprops. His briefing covered research on community noise, near field noise and en route noise. He discussed the diagnostic methods to measure blade pressures and blade temperatures. He also pointed out the advances made in the area of aeroacoustic prediction codes, and elaborated on the implications of turboprop research for tiltrotor aeroacoustics. His ***messages*** are summarized as follows:

1. Advanced Turboprop (ATP) prediction methodology is directly applicable to the "airplane" flight regime of the tiltrotor aircraft.
2. The aeroacoustics of tiltrotor configuration is simpler than that for turboprops if the tiltrotor configuration is restricted to single rotation, straight blades, low blade numbers, and subsonic tip Mach numbers.
3. ATP angle of attack methodology could work for the tiltrotor aircraft in the airplane mode, subject to validation for large angle of attack.
4. Aeroacoustic prediction capability developed for the advanced turboprop (ATP) is directly applicable to tiltrotor.
5. Angle of attack CFD and aeroacoustics prediction capability are critical for accurate tiltrotor noise prediction.
6. Blade pressure (temperature) measurements are essential to 3D code validation.
7. A significant ATP data base on turboprop community noise, near field noise, and en route noise exists, which could be used in code validation for tiltrotor aircraft acoustics.
8. Aeroacoustics flight tests are essential.
9. Based upon NASA Lewis experience for inflight noise tests, formation flight is a validated and valuable technique for inflight and far field noise source definition.

3.9 TILTROTOR NOISE PREDICTION METHODOLOGIES

Dr. **Nigel Peak** of the University of Cambridge described his and Professor Crighton's model for predicting propeller noise. He presented an asymptotic theory to estimate both near field and community noise from propellers. This method provides very large savings in computer CPU

time, especially for the calculation of near field noise (cabin noise). Peak and Crighton's methodology can provide a practical and accurate prediction scheme for some aspects of propeller noise at present. For example, it can predict the rotor only tones and also pylon-rotor interactions. Future developments could include prediction of noise produced by interaction between propeller and the wing.

Mr. **Robert A. Golub,** manager of Noise Prediction Technology at NASA Langley Research Center, gave an overview of the prediction development applicable to tiltrotor aircraft. The key program for noise prediction of rotorcraft is "ROTONET", which is one of the four dedicated prediction program in the large Aircraft Noise Prediction Program (ANOPP). The other three prediction programs are for predicting noise from propeller aircraft, conventional take-off and landing aircraft, and supersonic aircraft. Mr. Golub described a heuristic development plan for ROTONET resulting in four ROTONET codes, each successive code yielding an increase in prediction capability. The noise sources either incorporated or yet to be incorporated are related to thickness, loading, tip vortex formation, trailing edge, turbulence ingestion, engine, multiple rotors, rotor unsteady aerodynamics, main rotor/tail rotor interaction where applicable, blade vortex interaction, and quadrupole sources. Most sources applicable to helicopter noise have already been incorporated and sources unique to tiltrotor aircraft noise will be incorporated in planned future developments of the code.

ROTONET has the capability to predict basic blade interactions and multiple rotor acoustic interactions. Prediction agreement with data continue to show "good and bad news" about ROTONET capabilities. For example, Mr. Golub compared the measured and predicted data for a MDHC 500E helicopter and obtained good agreement at 45 degrees head-on approach, but in the aft arc, advancing sideline and retreating sideline, ROTONET underpredicted the noise. A good agreement was also found in the helicopter mode for the XV-15 data. The lack of symmetry of rotorcraft noises requires extensive data bases to be available for proper validation of ROTONET .

3.10 TILTROTOR FLIGHT TESTING

Mr. **David A. Conner** of the Aerostructures Directorate of AVSCOM and Mr. **Ken Rutledge** of Lockheed Engineering and Sciences Company, both working with the Acoustics Division of NASA Langley Research Center, described a comprehensive tiltrotor acoustic flight test program conducted by the Langley Research Center. The purpose of this program is to build a comprehensive, high-confidence data base of far-field acoustics for tiltrotor aircraft. Three specific objectives of the program are:

1. Calibration and validation of noise prediction codes such as ROTONET and WOPWOP.
2. Characterization and identification of vehicle systems noise mechanisms.
3. Evaluation of terminal area operations especially in relation to hover, and "low-noise" approach and departure procedures via nacelle tilt scheduling.

The acoustic tests were performed to acquire data during flyover, flyby, hover, and ascent and descent. Acoustics vans, reference microphones, weather vans, balloon vans, ground microphone arrays, and above-ground microphone arrays were used in these tests. During the acoustic data acquisition, the tiltrotor conversion corridor or operational envelop of nacelle angle versus airspeed included data points along the low, moderate, and high noise profiles. Conner and Rutledge described the acoustic data base acquired at Maypearl and also at Moffett Field. Maypearl acoustic data were acquired with the XV-15 tail number 702 with the original metal blades, while the Moffett field data were acquired using XV-15 tail number 703 with the Advanced Technology Blades (ATB). OASPL contours and EPNL data were presented. OASPL directivities at three tip speeds, namely, 645, 708, and 771 ft/sec, were presented for the XV-15 with ATB.

A comparison of predictions with XV-15/ATB acoustic data was also provided. ATB measured data were compared with OASPL predictions from WOPWOP using standard blade prediction. In general, measured levels were about 5 dB higher than those predicted.

Conner and Rutledge then discussed their recommendations for future work for analysis and flight tests. The recommendations for the analysis are summarized below.

1. Study source noise mechanisms.
2. Study fountain/ground plane effects.
3. Compare acoustic performance of ATB with standard blades.
4. Develop non-stationary techniques for ascent/descent regimes.
5. Resolve 3-D directivity character relative to RPM and weight effects.
6. Interact with ROTONET prediction team.

Plans for ***future flight tests*** are as follows:

1. <u>XV-15/ATB Flight Test Program at Crow's Landing (Summer 1992)</u>
   - Measure lower hemispherical acoustic characteristics.
   - Concentrate on terminal area flight conditions.

- Evaluate noise reduction flight procedures identified in NASA Research Announcements (NRA).
- Verify and further investigate noise mechanisms identified in Moffett Field test.
- Compare XV-15/ATB and original XV-15 blade noise characteristics.
- Correlate database with analytical methods.

2. V-22 Flight Test Program
   - Conduct comprehensive V-22 acoustic tests.
   - Measure lower hemisphere acoustic characteristics.
   - Investigate low noise operational procedures.
   - Identify critical noise problems in terminal area environment.
   - Correlate V-22 database with XV-15 database and analytical methods.

Dr. **Martin D. Maisel,** Chief of the Flight Experiments Branch at NASA Ames Research Center, presented a number of results based upon XV-15 tiltrotor acoustics flight experience, including the Advanced Technology Blades. He also provided 10 references on the subject of tiltrotor noise and presented a number of results from some of these references. A summary of conclusions drawn from his presentation is given below.

Ground Based Observations - XV-15

1. Noise levels are similar to those for a helicopter when in the helicopter mode.
2. The airplane mode is more than 10 dB quieter than helicopter or high nacelle angle tiltrotor modes at constant airspeed.
3. "Twin Peak" BVI waveform in tiltrotor mode requires further investigation.
4. Approach and departure noise levels are sensitive to nacelle angle and airspeed.
5. Approach noise is reduced with lower glide slope angles.
6. Flight techniques could be developed to significantly reduce terminal area noise.

In-Flight Observations - XV-15, Flush Microphones

1. Thickness noise is prominent in airplane mode in the vicinity of tip path plane.
2. Aft-cabin, forward flight noise levels are 5-8 dB quieter than hover mode.

Isolated Rotor Static Tests - ATB, XV-15, V-22

1. OASPL are sensitive to blade shape.
   - Far-field: ATB quieter than V-22, XV-15 blades at same $(C\tau)/\sigma$.

- Near-field: ATB, V-22 quieter than XV-15 blades.

2. DBA - Evaluation in work.
3. Difference between XV-15 & OARF sound levels requires investigation - possible fountain-flow effect.

Overall

1. A broad tiltrotor acoustic data base exists.

Finally, Dr. Maisel outlined the ***planned XV-15/ATB acoustic tests.*** They consist of:

1. Comprehensive terminal area evaluation (XV-15/ATB).
2. In-flight data acquisition.
3. Rotor/Airframe Airloads data measurements with pressure instrumented ATB.

Mr. **Clifford McKeithan** of the School of Aerospace Engineering and formerly the U.S. Army representative on the XV-15 program, presented a summary of the development and testing of the XV-15. He provided a comparison of tiltrotor performance with a range of other rotorcraft concepts. In particular, he compared the flight envelopes, hover efficiencies, power required (as a function of airspeed, minimum fuel flow loiter, vibration environment, hover noise levels, and maneuver envelope. He then described the XV-15 flight envelope, conversion corridor, power required in conversion and airplane, and crew station vibration levels and concluded that the XV-15 has successfully completed more testing (both technical and operational) than any other experimental aircraft today. Mr. McKeithan also gave an account of number of incidents involving the impact of the noise from XV-15. In all cases, it appeared that the XV-15 is relatively a low noise aircraft. He stressed that the tiltrotor concept has been proven to be sound and the results to date show that the concept is ready for application and is suitable for a wide range of missions.

3.11 TILTROTOR DESIGN AND OPERATIONAL CONSIDERATIONS

Mr. **Harry Sternfeld Jr.,** Manager of Noise Technology at Boeing Defense and Space Group Helicopter Division and his colleague Mr. **Harry Alexander** provided an overview of design and operational noise issues in the future of civil tiltrotors. Referring to "Civil Tiltrotor - Missions and Applications, Phase II: The Commercial Passenger Market," they talked about the cabin and community noise and its control through passive and active means. They also discussed lowering noise through increased spacing of fuselage/proprotor and through low noise blades and tip configurations. They provided a relative evaluation of cabin noise levels for current aircraft and

indicated that the V-22 cabin noise levels (untreated) are much higher than those of the existing (treated) aircraft and that substantial acoustical treatment will be required. They also showed that for a given V-22 rotor and tip Mach number and flight speed, the noise impinging on the fuselage can be reduced significantly by increasing the distance between the fuselage and the rotor tip. For example, by changing this distance from 24 inches to 36 inches, the noise impinging on the fuselage can be reduced by 3 dB. Sternfeld and Alexander then provided an analysis of the weight of the wing and cabin insulation required to achieve 78 dBA in the cabin as a function of tip clearance. They showed that a potential weight saving could be obtained by proper choice of clearance between the blade tip and the fuselage.They also indicated that further weight savings could be obtained by implementing active noise control methodology.

As pointed out by a number of previous speakers in this workshop, Mr Sternfeld and Mr. Alexander also highlighted the benefits of ATB design and those resulting from increasing the number of blades. They showed that the effect of increasing blade number is more obvious on dBC and the sum of harmonics, rather than on the PNL or dBA.

The dominance of very low frequency noise in the the tiltrotor noise spectrum is a major concern. This noise can dominate in the frequency range of 20 Hz to 80 Hz. Although the dBA levels may be low, because of the frequency weighing, the effects on building and household items, in terms of vibration and rattle due to relatively high Sound Pressure Levels at the blade passage frequency, can be particularly annoying.

Their concerns, and recommendations for noise reduction are summarized below:

Internal Noise

1. Since the tiltrotor frequencies are 1/4th of those of the turboprop aircraft, cabin levels of the order of 78 and 85 dBA may not be appropriate, and experimental research is required to establish what may be acceptable.
2. Active control techniques could minimize weight of the passive insulation, and developmental work is needed in this area.
3. Increased spacing between fuselage/proprotor is attractive for new commercial design.
4. Research and development on low noise blades /tip configurations is urgently needed.

Community Noise

1. Community noise can be a potential show stopper for tiltrotor aircraft.
2. The near-term solutions for abating community noise are:
    a. Follow noise abatement profiles in terminal areas.
    b. Incorporate low noise tip shaping, blade planform, twist, and airfoils in the current designs.
    c. Operate the aircraft at reduced tip speed in hover and conversion.
3. The long-term solutions for abating community noise are increasing the number of blades and implementation of active noise control techniques.

Mr Sternfeld and Mr. Alexander also provided recommendations for near term and far term noise research, as summarized below.

Near Term Research

1. Use simulation and air vehicle assets to develop low noise operational procedures and noise database.
2. Develop theory for noise prediction: hover, conversion, cumulative exposures.
3. Experimentally investigate tiltrotor blade pressures and acoustic sources (pressure instrumented blade).
4. Analytically and experimentally investigate blade noise reduction: sweep, tip shape, airfoil, planform, solidity.
5. Develop and test low noise rotor for a CTR-22C aircraft (civil version of a MV-22 Osprey).

Far Term Research

1. Continue attacking noise at its source.
2. Analytically and experimentally investigate noise and vibration implications of number of blades.
3. Conduct research on active suppression of external noise.

Mr. **Charles Cox**, Chief of Acoustics Technology at Bell Helicopter Textron, Inc., expounded upon the tiltrotor acoustics preliminary design and operational considerations. He discussed the low noise features of tiltrotor aircraft, compliance with noise criteria, design approach, flight

trajactory management, and research priorities. He presented typical noise spectra and noise contours for the XV-15.

A ***summary*** of the presentation by Mr. Cox is given below:

1. Tiltrotors in airplane mode easily meet helicopter flyover noise limits.
2. Tiltrotors also comply with helicopter take-off limits.
3. Tiltrotors just meet helicopter approach noise limits at some nacelle tilt/airspeed combinations.
4. Approach noise originates from near-parallel intersections of each blade with a previously shed tip vortex.
5. Tip shape concepts offer potential for diffusion of blade tip vortices, hence BVI noise.
6. XV-15 noise varies greatly within normal operating conditions.
7. Tiltrotor is 10-15 dB quieter in the airplane mode compared to the helicopter mode. Noise levels in the conversion mode fall in between the airplane and the helicopter mode.
8. Nacelle angle is a major operational variable affecting flyover noise of tiltrotor.
9. Delaying conversion to helicopter mode reduces XV-15 dBA noise contour area by 30%.
10. "Quietness" potential resulting from design changes in tip speed and planform/tip shape is high. The "quietness" potential from changes in the number of blades and blade area is low and from changes in airfoil is from low to moderate.
11. "Quietness" potential resulting from changes in flight trajactory management associated with nacelle tilt and airspeed is high. The gains from changes in glideslope are moderate.
12. Further research needs to be done in the area of analysis/design applicable to both models and vehicles through the following technology tasks:
    a. Low tipspeed maintenance.
    b. Tip vortex diffusion.
    c. Fountain effect minimization.
    d. Accessory noise control.
    e. BVI corridor definition.
    f. Steep approach criteria.
    g. Noise abatement (procedures) simulation.

Mr. **Charles C. Crawford**, Chief Engineer of the Aerospace Sciences Laboratory at Georgia Tech Research Institute, gave an overview of the direction that powered-lift (including tiltrotor) technology should take. Along the line of some of the other speakers at this workshop, Mr. Crawford provided a short historical perspective of the development of tiltrotor and discussed the

Phase I and Phase II tiltrotor studies earlier alluded to by Mr. Unger of NASA Langley. He also highlighted potential differences between tiltrotor aircraft and tiltwing aircraft. Referring to steep angle approaches with the two types of aircraft, Mr. Crawford indicated that the flight characteristic issues of the two aircraft are different.

Mr. Crawford's key points can be summarized as follows:

1. Providing stall-free approach corridor and conversion will be the biggest aerodynamic challenge for tiltwing configurations.
2. Different approach angles for different configurations may be appropriate.
3. Passenger comfort may limit both configurations to suboptimum noise abatement flight paths.
4. Bringing air carriers, the public, and local governments to an acceptable level of confidence for both tiltrotor and tilt-wing will be a major challenge.
5. Simulation technology should play a key role in determining environmental acceptability.

3.12 PROPER LAND USE PLANNING AND PUBLIC ACCEPTANCE

Dr. **Clifford R. Bragdon,** Professor of City Planning at the Georgia Institute of Technology, discussed the impact of tiltrotor aircraft noise in relation to three dimensional planning. Dr. Bragdon describes city and town planning as a professional discipline that addresses proactive planning with a goal of compatible development of land as a finite resource. He stressed that to be effective, planning should examine land use as a three-dimensional challenge. This involves aerial, surface, and subterranean aspects.

Dr. Bragdon mentioned that there are nearly 40 different types of land use strategies that can be applied to noise abatement and control. These strategies range from comprehensive master planning, zoning, capital improvements programming, environment site design and review, to building codes and sound insulation standards. Physical acoustics and psychoacoustics should be applied to understanding land management as well as political acoustics. To be effective, these strategies need to be actively integrated and supported by both the public (government) and private (corporate) sectors of society. Dr. Bragdon presented several examples where these principles of urban planning noise control are implemented.

Dr. Bragdon listed and discussed ***seven factors responsible for incompatible land use conditions.*** These factors are:

1. Lack of accurate cost/benefit analyses.
2. Population growth.
3. Population distribution.
4. Proliferation of certain noise sources.
5. Land encroachment where residential settlements often develop around transportation access points, creating incompatible land use impacts.
6. Inconsistent enforcement provisions.
7. Consideration of land use without examining operational controls around airports.

Dr. Bragdon then cited examples of land use planning control, technological trends of land use management, and their impact and control on vertical flight technologies.

Dr. Bragdon recommends a lengthy agenda of applied research to insure that vertical flight technology becomes an integral part of the urban multi-model transportation system. This list is summarized below:

1. Complete standardized inventory/acoustical library of vertical flight aircraft.
2. Characterize acoustical signatures: both airborne sound and vibration.
3. Develop acoustic metric characterizations for both single event and time phased activities.
4. Develop two and three dimensional graphical and acoustical simulations.
5. Prepare noise contour and geographic information systems (GIS) relational data bases and models.
6. Inventory both regulatory and advisory noise and land use controls instituted by governmental entities (i.e., local, metropolitan, and state).
7. Conduct territorial comparisons of aviation systems and human response in selected environments.
8. Develop land use and noise compatibility matrixes specifically for vertical flight aircraft.
9. Develop a model planning process and community interface, including case studies.
10. Integrate planning guidelines and standards with the actual development of vertical flight facilities.
11. Develop land use planning and noise control strategies and determine their relative effectiveness.
12. Develop conflict-resolution management strategies as applied to vertical flight development.
13. Utilize role playing and gaming for vertical flight planning and development.

Ms. **Deborah Peisen** of Systems Control Technology seconded Dr. Bragdon's contention that noise cannot be considered in isolation. We must be better prepared when integrating tiltrotor into urban transportation than we were with helicopters. Ms. Peisen maintains that as existing transportation conditions deteriorate, rotorcraft use will increase. Unfortunately, the capability of rotorcraft to go anywhere means that its noise goes everywhere. Without the development of a regulatory system concurrent with tiltrotor implementation, communities feel helpless and thus become reactive. She warned that without real public acceptance of helicopters, we are now proposing to introduce tiltrotors. We must use lessons learned from helicopters to avoid the same problems with community acceptance of tiltrotors. We must work with the community by designing an ordinance which gives the community a source of control. It creates a partnership in solving urban transportation problems. The ordinance bridges the gap between community interest and vertical flight industry interests. Ms. Peisen described various community concerns and recommended a number of action items to alleviate them.

These ***action items*** can be summarized as follows:

1. Use standard definitions to lessen the chance of misunderstanding.
2. Define roles of federal, state, and local government. (Ms. Peisen's presentation included a long list of suggested responsibilities and roles of these sectors of the government.)
3. Provide an adequate balance between land use and zoning.

Mr. **Ron Reber,** Manager of Commercial Tiltrotor Program at Bell Helicopter Textron, Inc., although scheduled to make a presentation could not be present personally. He had passed on his presentation to Mr. Jim McDaniel, Director of the FAA Vertical Flight Program Office. In presenting Mr. Reber's "talking points," Mr. McDaniel raised the same question raised earlier by Dr. Ahuja: "how good is good enough?" Mr. Reber's main points are summed up as follows:

1. A tiltrotor is quiet relative to a helicopter.
2. A tiltrotor does generate noise.
3. "How quiet is good enough?" must be answered.
4. Some communities are against rotorcraft operations.
5. Industry must make tiltrotor as quiet as possible.
6. Industry and the FAA must work together to minimize noise.
7. Tiltrotor service at airports is also noise sensitive.
8. Takeoff and landing at 90° to the active runway will often overfly populated areas.
9. Low noise procedures/steep approaches must be developed.
10. Away from the airport, noise control is still critical.
11. Operations over a highway access is a good way to mask noise.

12. Again, low noise procedures are needed to gain public acceptance.
13. Noise analysis, improved tip shapes, and lower tip speeds will all help the "cause."
14. Industry and government must also do public demonstrations to let people realize what actual tiltrotor noise is.
15. We must all work together to assure successful introduction of tiltrotors into the transportation system.

3.13 ROTORCRAFT FLOW DIAGNOSTICS

Dr. **Narayanan M. Komerath,** an Associate Professor in the School of Aerospace Engineering at Georgia Institute of Technology, presented ongoing efforts of rotorcraft flowfield diagnostics. In particular, he covered the applications of laser doppler velocimetry (LDV), hot-film anemometry, laser sheet visualization, wide-field shadowgraphy, phase-resolved pressure and velocity measurements, and spatial correlation velocimetry. Laser velocimetric measurements are routinely made at focal lengths of seven feet in the large rotorcraft testing facilities and wind tunnels of Georgia Tech. Examples of such measurements near a modern rotor tip and of vortex development over a rotor blade tip were given. Dr. Komerath presented extensive comparisons between experimental and computational flow data related to rotor flow fields. Other data presented by Dr. Komerath included: sharply varying inflow to a rotor, rotor-fuselage interaction, time-averaged velocity above airframe, and airframe surface mean pressure. Results of a recently developed, powerful technique of spatial correlation velocimetry that provides instantaneous velocity vectors were particularly interesting. Dr. Komerath also alluded to the Georgia Tech rotor/airframe interaction code and presented results documenting its validation against experiments. Dr. Komerath had two ***concluding statements:***

1. Diagnostic techniques are available for vehicle flow field for plane or point-wise measurements in rotor flows.
2. Overall flowfield of rotorcraft can now be predicted to provide the framework for acoustic prediction and control.

3.14 A WISH LIST OF R&D PROGRAMS IN TILTROTOR AEROACOUSTICS

In the last presentation of the workshop, **Dr. Krish K. Ahuja** presented a program wish list for research and development in the area of tiltrotor aircraft aeroacoustics. Dr. Ahuja has a joint

appointment in the research unit of the Georgia Institute of Technology as Head of the Acoustics Branch in its Aerospace Laboratory and in the academic unit as a Professor in the School of Aerospace Engineering.

Dr. Ahuja Presented the following ***four wish list items:***

Wish List #1: Determine the state-of-the-art for tiltrotor noise research.
Wish List #2: Examine the technology readiness of first generation products.
Wish List #3: Identify and resolve all research and development issues related to noise generation, propagation, detection, prediction, and reduction.
Wish List#4: Form a national tiltrotor noise committee/council.

Holding this workshop and the preparation of this report is part of item #1. Item #2 deals with a systematic and thorough assessment of noise technology readiness of the first generation civil tiltrotor. The following three programs are suggested:

1. Make a thorough assessment of noise features of competitive configurations (e.g., tiltrotor vs. tiltwing).
2. Conduct a well-controlled human and structural response test with simulated tiltrotor noise.
3. Conduct innovative research for interior noise control, including active noise control and mechanically-tuned absorbers; conduct laboratory and flight tests similar to those conducted recently for propfan assessment under the sponsorship of NASA-Lewis Research Center.

Under item #3, Dr. Ahuja outlined interactions between various research issues. He stressed the importance of building a highly versatile, small-scale tiltrotor aircraft model suitably scaled and instrumented for aerodynamic and acoustic studies. Dr. Ahuja listed the novel features of tiltrotor aircraft compared to a helicopter, gave a brief description of the so-called "polar correlation" technique to determine the location of a given source and urged its adoption to understand the sources of tiltrotor noise. He also talked about the so-called "installation effects" and gave examples of how these effects in conjunction with source location investigations have been examined in the past. Once a small-scale model as described is available, Dr. Ahuja suggested the following programs as part of wish list item #3.

1. Noise Generation

A. Theoretically, experimentally, and computationally evaluate various noise mechanisms of tiltrotor aircraft and rank them by relative importance. In particular, establish the effect of:

1. Different paths of tip vortices in the wake.
2. Higher disk loading.
3. Phasing between signals from two rotors.
4. Variable orientation of rotors and nacelles with respect to an observer.
5. Effect of wing-rotor wake interaction.
6. Blade loading differences due to higher twist.
7. Close passage of blade tips to the fuselage in airplane mode.

B. Conduct a systematic anechoic wind tunnel study on the installation effect of tiltrotor aircraft noise.

2. Noise Propagation

Assess the applicability of current sound propagation models to tiltrotor aircraft noise. Develop a code involving the effect of winds, atmospheric attenuation, ground effects, multipaths, and shadow zones. In addition, make extensive measurements of atmospheric turbulence and other meteorological parameters in conjunction with sound pressure levels to validate the propagation codes.

3. Noise Generation and Propagation

A. Develop computational aeroacoustics (CAA) in conjunction with mean flow CFD codes.

B. Conduct an aeroacoustic optimization study.

C. Develop a numerical simulation (movie) for flow and noise.

D. Examine noise footprints with suitable parametric variation.

4. Noise Detection (Measurement)

A. Conduct a laboratory survey with simulated tiltrotor aircraft noise to establish "how quiet is good enough".

B. Conduct a community survey when the full-scale vehicle is available.

C. Ensure that proper land use planning and operational procedure issues are included in both surveys.

5. Noise Control

A. Implement active noise control for interior noise and far field noise.

B. Implement active control through smart structures.

C. Combine active control and mechanically tuned absorbers.

D. Scrutinize noise control methods developed recently for advanced propfans.

6. Prediction

A. Develop a code which couples various aerodynamic, source, and propagation models.

B. Emphasize modularity and consistency between models, especially the ability to incorporate the most advanced models as they become available.

C. Correlate ROTONET and other helicopter noise codes with tiltrotor noise data and improve ROTONET.

7. Full-Size Vehicle Testing

Develop a measurement program in consultation with all interested researchers.

a. Industry

b. Government, to include military and civilian agencies.

c. University

8. Other Issues

A. Conduct a study to estimate the noise impact as a function of operational procedures.

B. Conduct a study of proper land use planning for vertiports (could well be done during planning for Olympics in Atlanta).

Finally, under ***wish list item #4***, Dr. Ahuja suggested that a national tiltrotor noise committee/council should be formed that should act as a center for disseminating information related to tiltrotor noise to all concerned researchers. Dr. Ahuja also proposed that future workshops similar to this one be held to continue this intiative and support noise R&D efforts.

Dr. K. Ahuja's choice of ***two key areas of government future funding*** were:

1. Build a versatile small-scale model and conduct a controlled parametric study to identify various noise generation mechanisms and test out various noise control methodologies. Also, use the available data to verify prediction codes.
2. Conduct a laboratory study with simulated realistic tiltrotor aircraft noise on structural and human response. (Will require low frequency noise sources.)

Dr. Ahuja's suggestion on where the **resources of the academic community** be spent were:

1. To support and encourage interaction with industry and government.
2. To develop an all-inclusive code.
    a. Conduct experiments with the small-scale model.
    b. Computer simulation of
        - Flight paths
        - Flow around the vehicle
        - Vibrations of the vehicle components
        - Acoustic wave visualization
        - Noise footprints

3.15 PANEL DISUSSION

A panel discussion was held after Dr. Ahuja's presentation.

SECTION 4

SUMMARY OF DISCUSSIONS DURING QUESTION AND ANSWER PERIOD

This section includes a summary of discussions that took place during the question and answer period.

4.1 FAA AND CERTIFICATION ISSUES

1. The overall budget of FAA for rotorcraft projects is in the vicinity of $9 million. This includes overhead, salaries, operating budget, and other programs.
2. Both the Vertical Flight Program Office and the Office of Environment and Energy at FAA are interested in noise work.
3. The current helicopter certification procedures are a nightmare. It is more difficult for Boeing to certify a helicopter than a B-767, and "it makes more money on B-767's." In fact, the current procedures for helicopters amount to a mini R & D program. In flying, one establishes the conditions for which one flies to establish the certification. On approach alone, in one case, over 100 approaches were flown to establish statistical validity. With the tiltrotor, there exists an additional degree of freedom, and the certification will be even more complicated compared to that for a helicopter. A simpler procedure is needed.

4.2 SIMULATION ISSUES

1. FAA is working with NASA to reduce the time necessary to develop terminal procedures by doing as much of that as possible through simulation. At present, FAA requires 200 to 300 hours of flight time just to test the new approach. It could take as long as eight years to get a totally new terminal procedure developed. Simulation is the key, and FAA is looking into what simulation might do for the certification process.
2. Simulation has potential, but to get anything believable in the sense of doing a certification for noise through simulation, we have a long way to go for tiltrotors.

4.3 NOISE STANDARDS FOR THE MILITARY

1. At present there does not exist a requirement for the military to meet a certain noise standard.
2. There exists a Memorandum of Agreement between the Defense Department and the FAA that, as the full-scale development flight program of V-22 proceeds, FAA can obtain noise data. The FAA will work with the military and NASA to coordinate additional noise data collection needed. This is to be done without jeopardizing the schedule of the military.

4.4 LOW-FREQUENCY NOISE OF TILTROTOR AIRCRAFT AND NOISE METRICS

1. Low frequency impacts need to be considered in the noise metrics.
2. If low frequency is going to be incorporated in the noise metrics for tiltrotor, helicopter noise is also going to be a consideration. If we can improve the noise levels, make it more of a good neighbor and more acceptable, then we're fulfilling our mission of advancing aviation and improving the national aerospace system.
3. A demonstration of noise comparison between a tiltrotor aircraft and an existing turboprop, say a SAAB 350, for the same altitude and air speed will be useful.
4. Georgia Tech has built a low frequency sonic boom noise simulator with a capability of generating 3 Hz to 4 kHz noise. This will be used to examine building and human response. The results from this study may be applicable to the impact of low-frequency tiltrotor noise on buildings and the community. This noise source will allow simulation of tiltrotor noise on buildings and human subjects.

4.5 WHAT DECIBEL LEVEL WILL BE ACCEPTABLE?

1. At present, there doesn't seem to be a specified decibel level for tiltrotor aircraft noise that will be acceptable to the community. It is envisioned that at a very minimum, this aircraft will have to meet the requirement for Stage 3. By the time this aircraft comes in, it may have to meet Stage 4, yet to be determined.
2. In a recent comparison (of tiltrotor noise) with Stage 3, it appeared to meet these requirements. But the issue with the tiltrotor aircraft is different. Unlike a National Airport type of landing, the tiltrotor landing is expected to take place somewhere downtown or somewhere in an urban residential area. As such, Stage 3 could be misleading here. Conventional Stage 3 for airplanes at an airport does not really apply to a downtown vertiport in a populated area.

4.6 TILTWING VERSUS TILTROTOR

1. NASA has assessed the noise performance of tiltwing versus the tiltrotor aircraft.
2. The tiltwing aircraft is expected to be noisier than the tiltrotor aircraft, but how much noise is not known at this stage.
3. The tiltwing aircraft will have more of a propeller type sound.
4. The tiltwing aircraft will have more high frequency sound compared to the tiltrotor aircraft.

4.7 MODEL-SCALE EXPERIMENTS

In relation to performing experiments using small-scale models, what really matters is the ratio of the tip speed to the induced velocity. The smallest wind tunnel model for tiltrotor appears to be that of Professor A. George of Cornell University.

4.8 AVAILABILITY OF FUNDS FOR R & D

No specific comments were made on the availability of funds for R&D in tiltrotor noise.

4.9 EN ROUTE NOISE

In relation to en route noise of advanced turboprop aircraft tested at NASA Lewis, it was mentioned that the most interesting thing in that data base is that there is no variability whatsoever in the noise signature on the fuselage. However, on the ground, there is a considerable amount of variability. A theoretical model needs to be developed to understand this behavior. (This relates to cruise noise of tiltrotor aircraft.)

4.10 V-22 NOISE DATA

1. Very little V-22 flight noise data is available.
2. Representatives of FAA will provide information to the V-22 Program Office on what needs to be done in terms of noise testing.

4.11 QUALITY OF DATA ACQUIRED STATICALLY

Some concern was raised by some of the workshop participants over the quality of airplane-mode and hover-mode acoustic data acquired statically. The proximity of the ground plane and the static operation can cause ingestion of considerable turbulence into the rotor plane that produces noise anomalies which may not occur in flight.

4.12 NOISE REDUCTION

Questions were asked on the potential decibels by which noise from tiltrotors could be reduced. It was felt that it was possible to achieve 10 dB reduction. From a pure design point of view, BVI could be treated for the approach case by diffusing the tip vortex.

4.13 VALIDATION TESTS

It was suggested by some that it will be difficult to get flying time on a V-22 or an XV-15 to conduct certain noise validation testing. One may have to resort to the use of helicopters as a validation tool.

SECTION 5
PANEL DISCUSSION

The panel discussion was chaired by Dr. Al George of Cornell University. The panelist were: Mr. George Unger, Dr. Marianne Mosher, Dr. Jim Yu, Mr. Harry Sternfeld, Mr. Charles Cox, Dr. Dan Schrage, and Mr. Steve Fisher.

A summary of the issues raised during the panel discussion is provided below.

5.1 FUNDING

Mr. Unger mentioned that the funding is rather tight to do a lot of things that should be done. He alluded to the fact that NASA cannot test the V-22 because " the only way to do it was to pay the manufacturer, and that's too expensive."

5.2 SECOND GENERATION V-22

Mr. Sternfeld expressed concern on hearing all the keying on the V-22 and the data derived therefrom. The V-22 was designed as a military vehicle. The driving attributes were payload, speed, size, maneuverability, and cost. Noise did not enjoy a very high priority on the V-22, what Mr. Sternfeld called a "first generation civil tiltrotor." The second generation civil tiltrotor will perhaps be a V-22 derivative of some kind. Mr. Sternfeld believed that the second generation can be quieter, if noise is given a higher priority.

5.3 INTERAGENCY COOPERATION

Mr. Unger would like NASA and FAA to work together and help each other out.

5.4 NOISE REDUCTION

1. Dr. Yu indicated that the area of active control needs to be speeded up and that there should be synergistic cooperation involving all sectors responsible for technology.

2. Referring to noise reduction methodologies, Mr. Sternfeld mentioned improved aerofoil development. Referring to the helicopter noise reduction related effort sponsored by NASA on tip shapes, higher harmonic control, and vortex modification devices, he indicated that some of them will be applicable to tiltrotors as well. He recommended that the issue of number of blades should be further researched, and encouraged all to stay inventive.

5.5 IS THERE A CIVIL TILTROTOR MARKET?

1. Mr. Cox indicated that the civil tiltrotor, if it ever comes about, is going to be developed much differently than what happened with the helicopter case of the last 20 to 30 years. In the case of the helicopter, a vehicle or vehicles existed before the civil helicopter market was created. The operators themselves ventured a lot of risk capital to create markets for the helicopter. With regard to the tiltrotor, " ---all the research was identified, and the needs identified in this conference (workshop), --." For tiltrotors, the markets will have to be developed first. " That market has to be developed really before the vehicle gets there. That may be impossible, but I think that's the challenge."

Mr. Cox also impressed upon the workshop participants that to begin developing the markets for tiltrotor aircraft, XV-15 and V-22's will be the only vehicles within a reasonable time frame. For the community to accept the tiltrotor, we have to convince them that its noise is acceptable. For the community to understand what the tiltrotor sounds like or compares to, the community needs a reference which will be comparable to current helicopters that they have experience with. So, part of the market creation is to educate the community about the features of the current tiltrotor.

2. Dr. Schrage expressed a need for pulling together en route planning, approach procedures, flight mechanics and control, and geographical information systems to create a civil tiltrotor market and to educate the community. An infrastructure within the government working with industry and universities needs to be put together quickly. Dr. Schrage did not think that there will be a civil tiltrotor transport in operational use before the end of this century.

3. Mr. Fisher agreed with the earlier statements by others that one has to have the market there. He also agreed that the infrastructure, the systems, the routes, the facilities, the air traffic control, the pilot techniques, etc., have to be in place before the industry is willing to build the aircraft and the carriers are willing to buy them. Mr. Fisher mentioned the FAA's goal is to be able to pool resources and be able to get the synergy necessary. His interests lie in being able to identify those

requirements where joint use can be made of the expertise available in all sectors: government, industry, and academia.

4. Major Losier contradicted an earlier statement by Dr. Schrage about when a civil tiltrotor aircraft could be built. He implied that it could be built pretty quickly so long as the infrastructure problem was solved. He suggested that there are a number of bottlenecks out there which should also be looked at. Maj. Losier stressed that any technology development dealing with acoustics should be timed with the development of the infrastructure. He then urged all concerned to match acoustics efforts with all other efforts.

5. Mr. Fisher outlined a summary of the plans in the noise area for the next five years concurrent with terminal approach procedures. He indicated that the terminal approach is the tip of the iceberg to the next step, which is transition. The knowledge gained from noise research and development must feed into all the work related to infrastructure requirements. Mr. Fisher also alluded to the sensitive nature of tiltrotors in the eyes of the major carriers and their near term major airport expansion plans.

6. Continuing on the subject of the challenges facing the development of a marketable civil tiltrotor, Mr. Sternfeld pointed out that a parent company does not launch a new program until it has signed customers. He warned that even in the case of Boeing 777, it was launched only after about two airlines had signed. Most helicopter operators are financially not as strong as the airline operators. They may not be willing to take "that kind of venture." He then advised that "somebody's going to have to start the ball rolling and actually demonstrate that money can be made---."

7. Dr. Schrage mentioned that the secret of success is to get the entire aviation community behind tiltrotor. He argued that to succeed, there has to be an effort on the part of the government to put enough funds to get tiltrotor off and running. This should also be done without jeopardizing the existing elements of aviation industry, especially the commuter industry. The tiltrotor market should thus be sold as a new form of transportation, and not as an alternative to existing commuter transport.

8. Mr. Fisher agreed with the fact there are a number of different risks in building the tiltrotor aircraft. These risks are faced by the FAA, NASA, by the local communities, and by some of the regional authorities who are going to be putting their prestige and support behind this kind of joint

operation. "--there is an operational risk, there's a certification risk, and I think there is a technical risk,---"

5.6 TILTWING VERSUS TILTROTOR

1. Some discussion was also held on the subject of the tiltwing. Mr. Fisher pointed out that the charter of his vertical flight program office was "vertical flight" and not just "tiltrotor." He felt that it was valid that they start looking into tiltwing. He would like to approach tiltwing noise as well, building off of the initiative already started in the tiltrotor area. FAA has not identified a specific tiltwing program, but it is something that they would be interested in.

2. Mr. Unger said that NASA had a different view than that of FAA on the subject of tiltwing. If FAA receives a certification application, it has to respond. NASA, on the other hand, has a little more liberty in deciding its priorities. NASA has chosen to focus on those things where it can best do its work and make a difference. Based upon the market for tiltrotor versus tiltwing, NASA has opted for tiltrotor. Tiltwing can benefit from a lot of work being conducted in the area of tiltrotors, and NASA will support tiltwing research, but not as a major effort.

3. An interesting question was asked by the Panel Chairman, Prof. George: "If you were starting all over again, and the V-22 wasn't there, would you look at tiltwing?" The response of both Mr. Cox of Bell Helicopter and Mr. Sternfeld of Boeing was negative. Mr. Cox's rationale behind his response was related to design from an aerodynamic point of view and also his concern about higher noise from the tiltwing. Mr. Cox was apprehensive about the solution of the stall problem of the tiltwing during conversion. Also from a noise point of view, Mr. Cox mentioned that the disk loading will be very high for the tiltwing, which will make it very noisy, and there is very little that can be done in that high powered transitional corridor. Mr. Cox also indicated that the market for tiltwing is very limited.

4 Mr. Sternfeld of Boeing Helicopter supported Mr. Cox's contention on the limited market for tiltwing. It will serve a smaller passenger market. Mr. Sternfeld also pointed out that a smaller tiltwing meeting a market for fewer passengers than the V-22 or a tiltrotor isn't necessarily noisier. But if one compares size for size, same weight, the tiltwing will be noisier.

5 In connection with the larger size tiltrotor, Dr. Schrage brought up a very interesting feature in favor of the tiltwing. " When you get bigger and bigger, you have the option of putting four props

on a tiltwing. You can't put four rotors on a tiltrotor very easily." Mr. Unger, however, had arguments to counter these remarks by Dr. Schrage.

5.7 OTHER ISSUES

1. A question was raised by Dr. Ahuja : " ---has anybody considered using ducted propeller---." The response received was that it has been considered but it is not a viable choice for tiltrotor application.

2. In relation to grass root support from the public for tiltrotor technology, Mr. Fisher would like to know how best to get the government to take the lead.

5.8 NOISE PREDICTION

Moving on to the issue of tiltrotor noise prediction, it was mentioned that we are probably half way to being able to predict noise from a V-22 type vehicle. Because of the lack of acoustic data, only a limited validation of the prediction codes has been made to date.

5.9 THE BIGGEST CHALLENGE IS BVI

1. Referring to rotorcraft noise, Mr. Golub named BVI as the the biggest challenge in prediction of noise, and perhaps the one that holds the key to making it really quiet.

2. In relation to BVI, it is very difficult with the current state of the art to predict the position and the strength of a tip vortex. These aerodynamic parameters need to be understood and predicted before the acoustics can be modeled. It will take creative, intelligent people along with big computers to resolve this issue. Mr. Unger mentioned subsequently that the understanding of vortices is not a unique problem for the rotorcraft community alone; the fixed wing researchers are just as concerned. It affects capacity, and it affects separation between aircraft during approach and take-off.

3. NASA Langley is sponsoring efforts at reducing BVI with three companies at present: Boeing Helicopter, McDonnell Douglas, and UTRC. The initial effort is focused on analysis through CFD to establish if there is potential for controlling BVI. The possibility of funding the verification will be considered later.

4. It was recommended that all reseachers working on BVI should become part of a task force and work together for a period of a couple of years. Dr. Yu recommended that a crash program involving university innovative concepts on BVI noise reduction be initiated.

5.10 DESIGN FOR NOISE CAPABILITY

1. Dr. Yu stressed that while we are moving forward with the civil application, we should also keep military requirements in mind (during research and development). He also mentioned that the future challenge of the rotorcraft/helicopter is really in the civil sector, and the noise issue will become a more important design issue than ever before.

2. Dr. Yu also reemphasized the need to develop, in the near term, a preliminary or the first version of the design for noise capability. " I personally think that's one area that has been grossly under-explored in rotorcraft aeroacoustics research. NASA will step up research in this area in future years."

5.11 FUTURE WORK

1. Mr. Unger wanted to make sure that in addition to BVI, there are other concerns that one can work on a near-term derivative of the V-22. Some of these concerns are: does the pilot have to hear the noise; does he have to have a noise dial in his cockpit that he has to worry about; how do you sense noise from the outside and display it to the pilot; does it all have to be automatic; does it increase his workload?

2. Mr. Unger also pointed out the need to have a model with pressure instrumented blades. Further work needs to be done to address the cockpit noise issues for noise abatement maneuvers.

3. Dr. Schrage gave his impressions of the workshop. His recommendation for future work was in the area of operations, different flight paths, trajectories and their impact on noise footprints and other kind of environments. He expressed his views on the importance of simulation studies.

SECTION 6
SUMMARY AND RECOMMENDATIONS

This workshop was the first of its kind and all in attendance found it quite productive. There was a general consensus that such a workshop should be held again within 12 months.

Summarized statements of the important issues raised during the presentations, during the question and answer period, and during the panel discussion have already been provided in the previous sections. Only an overall summary is provided below. Also, Table 1 provides a summary of the emphasis of each presentation and an indication of what other aspects of tiltrotor noise were covered in each briefing.

6.1 NOISE GENERATION

The biggest challenge in the area of understanding rotorcraft noise generation is to be able to predict the aerodynamics of blade vortex interaction (BVI). It is recommended that concentrated effort on the part of all parties concerned be made to understand BVI and noise therefrom.

6.2 NOISE PROPAGATION

This topic was not a major item of discussion. It was, however, pointed out that propagation of low frequency noise is not well understood. Its impact on en route noise will have to be determined.

6.3 NOISE DETECTION (CERTIFICATION)

Low-frequency noise associated with tiltrotor noise was discussed considerably. It is recommended that its impact on the community, passengers, and structures be determined. It is also recommended that the decibel level from tiltrotor aircraft that will be acceptable to the community be established as soon as possible. A knowledge of this level will determine the direction of other research efforts, such as the degree of noise reduction needed for the tiltrotor to be acceptable. It is also recommended that low frequency be incorporated in the noise metrics.

6.4 NOISE PREDICTION

Considerable work needs to be done in the area of noise prediction. A good quality acoustic data base is needed to validate prediction codes. It is recommended that in future full-scale acoustic data acquisition, all key personnel working on noise prediction be consulted.

6.5 NOISE REDUCTION

A number of suggestions were made during the workshop on methods of noise reduction. They include: increased spacing of fuselage/proprotor, active control techniques, low noise blades/tip configurations, improved airfoil shape, increased number of blades, tip vortex diffusion devices, reduced tip speed, blade planform, variable diameter blades, and others. It is recommended that a systematic study be conducted to evaluate and rank all of these and other methods of controlling tiltrotor noise.

6.6 TILTROTOR VERSUS TILTWING

A systematic comparison of noise generated by the two main competing configurations, tiltrotor and tiltwing, has not been made, although a number of differing arguments were presented in favor of one against the other. It is recommended that a thorough comparison be made to evaluate the noise performance of the two configurations.

6.7 CERTIFICATION PROCEDURES

If the current helicopter certification procedures are any example, the certification procedures for a tiltrotor aircraft may prove to be a nightmare. It is recommended that a simpler procedure of certification be implemented.

Current thinking that compliance with Stage 3 may be acceptable could be totally misleading. Conventional Stage 3 for airplanes at an airport does not really apply to a downtown vertiport in a populated area.

6.8 SIMULATIONS

The time necessary to develop terminal procedures can be reduced considerably through simulation. It is recommended that work on simulation be continued even though to get anything believable in the sense of doing certification of noise for tiltrotors may take a long time.

6.9 SMALL-SCALE MODELS

There exists a dire need for an instrumented small-scale model. It is recommended that one such model be built and be made available to all of the research community. The blades of the model must be instrumented.

6.10 DESIGN FOR NOISE CAPABILITY

NASA Langley's effort on "design for noise capability" is an attractive effort and should be stepped up in the future.

6.11 TILTROTOR MARKET, INFRASTRUCTURE, AND ACOUSTICS R & D

A civil tiltrotor market is highly dependent upon the infrastructure, the systems, the routes, the facilities, the air traffic control system, the pilot techniques, etc. It is recommended that requirements be identified where joint use can be made of the expertise available in all sectors: government, industry, and academia. It is also recommended that preparations be made to educate the community about the features of the current tiltrotor.

It is also recommended that any R & D in tiltrotor acoustics be closely timed with the development of the infrastructure. In addition, all acoustics efforts should be timed with all other efforts.

6.12 LAND USE PLANNING AND PUBLIC ACCEPTANCE

Thorough use should be made of the principles of urban planning for noise control. It is recommended that efforts be made to get the public behind the tiltrotor program by working with the community, designing an ordinance that gives the community a means of control.

6.13 INTERACTION WITH THE ACADEMIC COMMUNITY

Interaction with the academic community needs to be increased. It is recommended that the resources of the academic community be used to develop an "all-inclusive" code. A computer simulation should be developed and verified with high fidelity experiments to incorporate flight paths, flow around the vehicle, vibrations of the vehicle components, acoustic wave propagation, and noise footprints as a function of operating conditions and geometrical variations. It is also recommended that a crash program involving university innovative concepts on BVI noise reduction be initiated.

6.14 LESSONS FROM PROPFAN RESEARCH

Advanced turboprop (ATP) prediction methodology is directly applicable to the "airplane" flight regime of tiltrotor aircraft. ATP angle of attack methodology could also work for tiltrotor aircraft in the airplane mode, subject to validation for large angles of attack. It is recommended that full use be made of the rich knowledge available in the area of propfan acoustics.

6.15 OTHER ISSUES

A number of other issues are addressed in the bulk of the text of this report. It is recommended that due consideration be given to them also for the ultimate successful launching of the civil tiltrotor in the market place.

6.16 SECOND WORKSHOP ON TILTROTOR AIRCRAFT NOISE

It is recommended that the subject of tiltrotor aircraft noise be revisited on a later date by holding a second workshop within 12 months.