# TILTROTOR AEROMECHANICS PHENOMENA: REPORT OF INDEPENDENT ASSESSMENT PANEL



# FINAL REPORT

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# TILTROTOR AEROMECHANICS PHENOMENA: REPORT OF INDEPENDENT ASSESSMENT PANEL FINAL REPORT

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**Submission to:** **Rear Admiral J. A. Cook**

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**Naval Air Systems Command**

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# I. EXECUTIVE SUMMARY

# EXECUTIVE SUMMARY

The U.S. Navy requested that NASA perform an independent assessment of tiltrotor aeromechanics phenomena that might adversely impact the safety or performance of the V-22. To comply with this request, NASA formed an independent panel of experts from industry, academia, and government. At the request of the Navy, the Panel focused on vortex ring state and Autorotation but later enlarged its review to consider other low speed aeromechanics phenomena that it felt were pertinent to the V-22 at its present stage of development. The following aeromechanics phenomena were considered:

- Vortex Ring State
- Power-Off (All Engines Inoperative) and Autorotation
- Shipboard Compatibility
- Low Speed Flight / Wind Azimuth Envelope
- Formation Flight and Air-to-Air Refueling
- Hover Performance

In the main body of the report these tiltrotor phenomena are described and highlights of key information are presented, followed by the findings and recommendations. Some additional non-aeromechanical issues are also discussed.

The principal conclusion of the Panel is that there are no known aeromechanics phenomena that would stop the safe and orderly development and deployment of the V-22.

Although some restrictions have been imposed on the operation of the vehicle, the Panel expects that most of these will be removed or reduced in scope through the completion of the flight test program. With appropriate test buildup, procedures, and identified recovery techniques, it is believed that it will be safe to conduct the planned flight tests. Consequently, the Panel recommends that the development flight test program be resumed without delay, and it fully endorses the proposed Integrated Test Team Flight Test Program. The Panel believes that the V-22 operational envelope can be expanded by completing the planned flight testing and by implementing the recommendations set forth in this report.

In light of these significant developmental flight test requirements, and a desire for enhanced productivity, it is suggested that additional testing assets (aircraft, personnel, and resources) be made available to the Integrated Test Team to ensure timely completion of the flight test program.

The Panel was privileged to receive briefings from a number of pilots who have tested the V-22, and their enthusiasm for the aircraft and its capabilities is recognized as a most important endorsement of the program. The Panel believes that when fielded, the V-22 will truly revolutionize the role of transport aircraft in the defense of our country. The Panel therefore strongly supports the completion of the V-22 Program. Given the evolving mission of our armed forces in the 21$^{st}$ century, the Panel believes that this vehicle should be deployed at the earliest opportunity.

The Panel identified two categories of recommendations, the first being those high priority matters that the Panel felt were very important and that should be pursued as soon as practical, and the second being those the Panel felt should be considered as part of a normal vehicle enhancement program.

# High Priority Recommendations

### VORTEX RING STATE

- Resume and complete flight testing in accordance with Test Request 64 (TR-64) without delay.
- Revise the display of rate-of-descent information to the flight crew. The scale should be usable by the crew for observing rate-of-descent flight restrictions.
- Expand TR-64 to include tests in the 40–60 knot range to more accurately determine the vortex ring state boundary.
- Conduct additional flight tests to determine the extent of the dynamic maneuvering effect on the vortex ring state boundary, if TR-64 is insufficient to do so.
- Use flight test results to modify current vehicle operational rate-of-descent flight restrictions, if required.
- Determine if a warning system is needed; if so, develop a system that will avoid frequent and obtrusive alarms.
- Once adequate flight test and any supporting wind tunnel data are available, incorporate a vortex ring state model into flight simulators for avoidance and recovery training.

### POWER-OFF (ALL ENGINES INOPERATIVE) AND AUTOROTATION

- Conduct flight tests to develop one-engine-inoperative and height-velocity diagram databases.
- Perform simulation and additional flight tests, if required, to develop procedures that maximize the probability of achieving a safe landing in the one-engine-inoperative condition.
- Demonstrate in flight one-engine-inoperative conversion and reconversion.
- The ability to perform a personnel survivable all-engines-inoperative landing under all flight and weight conditions in helicopter mode should not be a mandatory program requirement. The Panel believes this requirement is not met by any transport helicopter in military use today.

### SHIPBOARD COMPATIBILITY

- Conduct further shipboard testing to expand the shipboard operations dynamic interface envelope.

- Conduct the engineering investigation, testing, and development needed to eliminate the requirement for a limitation on other aircraft landing at spots closely ahead of a V-22 with rotors turning. Include in the investigation possible stiffening of the V-22 landing gear system, increased roll authority, and other possible modifications to the flight control system that could improve overall shipboard handling.

### Low Speed Flight/Wind Azimuth Envelope

- Conduct additional flight tests of the V-22 operating in low speed flight around the azimuth to expand operational flight restrictions, and to investigate flight control procedural techniques including nacelle control.

### Formation Flight and Air-to-Air Refueling

- Conduct the planned flight testing (TR-65) of two V-22s in formation flight, emphasizing typical mission maneuvers in helicopter and conversion mode. Extend these tests to include more than two V-22s (up to six, if practical).

- Develop operationally acceptable formation flight procedures and separation limits for takeoff, approach, landing, cruise, and aerial refueling.

### Hover Performance

- Complete flight tests to define hover performance throughout the operating range of the aircraft, particularly at high altitude and in hot and cold weather environments.

## Vehicle Enhancement Recommendations

### Vortex Ring State

- Investigate increased roll control authority to provide greater vortex ring state margin and control of aircraft in the event of roll-off in high rate-of-descent flight.

- Evaluate the resulting flight envelope against V-22 mission requirements; consider envelope expansion.

### Power-Off (All Engines Inoperative) and Autorotation

- Revised airplane mode one-engine-inoperative and all-engines-inoperative procedures and training should be developed. The V-22 requirements (specification SD 572-1) should be reviewed regarding power-off operation and revised to reflect the preferred airplane mode landing.

The possibilities of improving all-engines-inoperative airplane mode glide (e.g., auto-flap settings for best glide) should be examined.

### Low Speed Flight/Wind Azimuth Envelope

- If flight testing warrants, conduct a wind tunnel test, as soon as practical, to (1) investigate the aerodynamic phenomena of low speed flight regarding both critical

azimuth issues and pitch-up-with-sideslip, and (2) develop aerodynamic modifications that can allow an expansion of the flight envelope.

- Investigate increased longitudinal control authority, particularly with regard to minimizing pitch-up-with-sideslip.

- Conduct investigations to determine if an affordable low air speed and/or sideslip indicator can be developed for operational use.

### Formation Flight and Air-to-Air Refueling

- Investigate the feasibility of flight control system enhancements to minimize objectionable aircraft response characteristics during interaction with lead aircraft wake.

### Hover Performance

- Investigate why actual vehicle hover performance is different from that predicted based on isolated rotor tests.

### Flight Control System

- Investigate modifications of the flight control system to increase control authority with emphasis on authority about the roll axis. Special attention should be given to the difficult flight conditions experienced in shipboard operations, low speed flight, and formation flight.

### Communications: Deficiency Reporting Process

- Review the Deficiency Reporting Process and require expert independent deficiency classification (Part I, II, and III) in a timely manner.

# II. DETAILED REPORT

# OVERVIEW



The U.S. Navy requested that NASA perform an independent assessment of tiltrotor aeromechanics phenomena, focusing on vortex ring state characteristics and autorotation. This request was transmitted as a letter, dated 24 May 01, from Rear Admiral J. A. Cook to Dr. Henry McDonald, Director of NASA Ames Research Center (see Appendix A). Dr. McDonald formed and chaired a Panel of twelve vertical flight experts from government, academia, and industry; none of the Panelists had direct V-22 conflict of interest. The Panel members (with a brief description of their experience) as well as a brief biography of Dr. McDonald are shown in Appendix B. Four of the Panelists are members of the National Academy of Engineering.

The charge for the independent assessment was established as follows:

- Develop a comprehensive assessment and summary of tiltrotor aeromechanics phenomena (vortex ring state, autorotation, low speed maneuvering, etc.) that could be encountered by tiltrotor aircraft and that might be detrimental to its safe and efficient operation
- Address the present state of understanding of the phenomena from theory and experimental results through flight testing, operations, and training
- Formulate specific Findings and Recommendations for the V-22

A working group Technical Team (Appendix C), of active vertical flight and tiltrotor experts from the government and industry, was assembled to gather information for the Panel to

assess. Membership included individuals from the V-22 Integrated Test Team, Operational Evaluation team, engineers, and tiltrotor pilots. Initially, the Technical Team formulated four questions to be addressed regarding tiltrotor aeromechanics phenomena (Appendix D). In addition, Dr. McDonald drafted eleven questions specific to the V-22 for the Technical Team to consider (Appendix D).

The Technical Team heard briefings (Appendixes E and F) on the MV-22 and CV-22 Requirements, and Developmental and Operational Evaluation Flight Test experiences. Bell Helicopter Textron and Boeing personnel presented the manufacturers' perspectives. NASA researchers presented the state of understanding of the tiltrotor aeromechanics phenomena from theory through experiments to flight research experience with the XV-15 tiltrotor research aircraft.

The Technical Team also sought relevant views from outside of the federal government. This resulted in hearing twelve invited presentations from six universities, Continuum Dynamics, Inc., and the Institute for Defense Analysis (IDA) (Appendix G). The university presentations were primarily focused on the vortex ring state and autorotation. Relevant theories, experimental data, analyses, computational fluid dynamics (CFD) calculations, and research recommendations were presented. A briefing on a potential vortex ring state warning system was also given. Continuum Dynamics, Inc., presented CFD calculations of tiltrotor aircraft approaching and in the vortex ring state. Dr. Arthur Rivolo of IDA, presented his assessment of the findings of the report "Combined Operational Test and Evaluation and Live Fire Test and Evaluation Report on the V-22 Osprey," conducted for the Director of Operational Test and Evaluation.

Based on the information collected and discussed, the Technical Team compiled the tiltrotor aeromechanics phenomena information and presented it to the Panel. The Panel also heard presentations on the Department of Defense V-22 Blue Ribbon Panel and the V-22 Director of Operational Test and Evaluation reports. From the Panel discussions and deliberations, an initial set of Findings and Recommendations was drafted by the Technical Team and presented at the second meeting of the Panel. After numerous reviews and refinements, the Panel strongly endorses the Findings and Recommendations that are presented in this report.

The Panel focused on tiltrotor aeromechanics phenomena that are pertinent to the V-22 at its present stage of development. The aeromechanics phenomena that were identified are the following:

- Vortex Ring State
- Power-Off (All Engines Inoperative) and Autorotation
- Shipboard Compatibility
- Low Speed Flight / Wind Azimuth Envelope
- Formation Flight and Air-to-Air Refueling
- Hover Performance

In addition, the Panel feels that the Flight Control System is an important factor in most of the phenomena discussed in this report, and modifications to the Flight Control System should be considered.

Although not originally tasked to identify non-aeromechanics issues, an important communications issue regarding the deficiency reporting process has also been identified.

In the Aeromechanics Phenomena: Description, Findings, and Recommendations section, the identified tiltrotor phenomena are described, and highlights of key information are presented, followed by the specific Findings and Recommendations. These recommendations are placed in two categories. In the first category are recommendations that the Panel feels are of high priority and should be pursued without delay. In the second category are recommendations that should be considered as part of a normal vehicle enhancement program. Some of the identified future tiltrotor research opportunities are mentioned in the Key Information subsection.

Dr. McDonald presented a pre-decisional briefing of the Panels' efforts to the V-22 Executive Committee, the Offices of the Secretaries of Navy and Air Force and to the Under Secretary of Defense for Acquisition, Technology, and Logistics, Pete Aldridge. A schedule of the briefings is shown in Appendix E.

The Panel strongly supports the completion of the V-22 development and deployment. The tiltrotor aeromechanics issues discussed herein are serious and must be pursued diligently and without delay. However, with the competence and professionalism observed in both the government and contractor personnel entrusted with the engineering development and qualification program, and given the required level of resources, none of these issues should preclude a satisfactory and timely transition to operational testing and fielding.

Although some restrictions have been imposed on the operation of the vehicle, the Panel expects that most of these will be removed or reduced in scope through the completion of the flight test program, and by implementing the recommendations that have been presented in this report. With appropriate buildup, test procedures, and identified recovery techniques, it is believed that it will be safe to conduct the planned flight tests. Consequently, the Panel recommends that the development flight test program be resumed without delay and fully endorses the proposed Integrated Test Team Flight Test Program.

A significant amount of flight testing needs to be completed. Additional recommendations by this Panel regarding flight tests are made under the headings of the specific phenomena discussed. In light of these remaining developmental flight test requirements and a desire for enhanced productivity, it is suggested that additional testing assets (aircraft, personnel, and resources) be made available to the Integrated Test Team.

The Panel was privileged to receive briefings from a number of the pilots who have tested the V-22, and their enthusiasm for the aircraft and its capabilities is recognized as a most important endorsement of the program. When fielded, the V-22 will truly revolutionize the role of transport aircraft in the defense of our country.

# VORTEX RING STATE



## DESCRIPTION

Vortex ring state is an aerodynamic phenomenon that may be encountered by all lifting rotors in descent when the downward thrust-induced velocity is opposed by the approximately equal upward free-stream flow. It has been found to occur in pure vertical descent or in descent at relatively low airspeeds (below 60 knots). Since it is related to thrust-induced velocity, the rate-of-descent at which it occurs depends upon the rotor's disk loading. It follows that for a tiltrotor, which is characterized by high disk loading, that vortex ring state would occur at a high rate-of-descent relative to that of conventional helicopters.

Vortex ring state is characterized by the absence of a definite slipstream and the presence of large recirculating flows. It is a fundamentally unsteady flow condition that is further characterized by thrust oscillations, thrust reductions (in the absence of control inputs), control response reduction, and, ultimately, an unstable trend of thrust versus rotor disk angle of attack.

There has been very little research on vortex ring state. Much of what is known is based on old helicopter (35 years or more) flight test and wind tunnel work. This has been primarily a result of the lack of significant numbers of vortex ring state-related accidents with helicopters.

## GOAL

Establish safe flight envelope limitations and low speed/descending flight procedures that have minimal impact on operations.

# KEY INFORMATION

From the information assessed, the Panel has confidence that the V-22 can be operated safely and effectively when used within prescribed limits while meeting its mission requirements.

- The flight testing that has already been conducted is sufficient to conclude that vortex ring state does not prevent the V-22 from being safely and effectively utilized. The currently imposed flight restrictions are considered very conservative, yet would be operationally acceptable.

- The rate-of-descent limit, 800 feet per minute (for horizontal airspeeds of less that 40 knots) provides a very large safety margin from the areas where vortex ring state initiated control problems were encountered (descent rates greater than 2000 feet per minute).

- The utility of the V-22 will be considerably enhanced when the flight restrictions can be expanded from the current limits. The testing conducted to date is not sufficient to completely establish these expanded operational boundaries.

- A tiltrotor aircraft, when deep within the vortex ring state region, can encounter uncommanded roll motions due to its side by side proprotor configuration.

- A highly effective recovery technique from uncommanded roll motions has been established and verified by recent tiltrotor flight tests. The procedure is as follows: (1) tilt the nacelles forward at maximum rate for 2 sec to 80 degrees; (2) pitch down (proprotor tip path plane), using forward longitudinal cyclic pitch control; and (3) accelerate with fixed Thrust Control Lever (TCL) if altitude permits.

  - While exploring the vortex ring state region (vertical descent rates of ≈ 3000 feet per minute), recovery from roll-off using the technique was attained (6 events) within 400 - 1200 feet of altitude (4-11 seconds of elapsed time). A minimum-altitude-loss recovery technique has not been explored.

    + Roll-off recovery time/altitude is defined as the period from the beginning point where the roll-off begins to the point of recovery where there is a return to wings level.

    + It should be noted that if recovery were initiated at the first signs of vortex ring state, altitude loss would be minimized.

- The current airspeed sensing and display system does not provide the pilot with adequate situational awareness concerning entry into the vortex ring state flight regime.

- Although natural vortex ring state cues appear to exist and appear to be repeatable, they may not be sufficient for pilots to recognize when the workload is high.

- The Panel recognizes the possible need for a vortex ring state warning system. Research to develop a simple system that will increase the pilot's situational awareness should be started as soon as possible. Future research efforts should address the following:

  - Determine if a sufficiently accurate and reliable low-airspeed measurement can be utilized.

- Assess the vortex ring state cues such as vibration, noise, and flight control system computer activity that are observed in flight tests in order to understand their usefulness to the pilot under high workload conditions.

- Consider the impact of training and natural aerodynamic cues on recognition of the approach to the vortex ring state. The improved or additional display of information to enhance the pilot's situational awareness must be evaluated.

- Conduct an overall assessment of the need for a vortex ring state approach on-set warning system. If such a warning system is necessary, develop one that will be acceptable to the pilots, and include sufficiently accurate air data and the effects of maneuvering on the vortex ring state envelope (yaw and roll rate are important).

- Although qualitatively similar, the behavior of isolated proprotors (tiltrotors) in the vortex ring state is quantitatively different from that of isolated helicopter rotors, because of higher disk loading, blade twist, and proprotor solidity (for more information see Appendix H).

- The general characteristics of the vortex ring state of proprotors are known, although the engineering community did not anticipate the severity of the consequences for roll control on the side-by-side tiltrotor arrangement.

  - Two proprotors do not always experience the same air flow state; especially when sideslip or other asymmetric conditions are encountered. In certain conditions this can cause an uncommanded roll which, in exceptional circumstances such as vortex ring state, may require a very aggressive response from the pilot.

- The detailed aerodynamics of proprotors in the vortex ring state is not completely and quantitatively understood and the vortex ring state characteristics of the tiltrotor (two proprotors, wing, and fuselage) have not been sufficiently explored. For instance,

  - The precise vortex ring state boundary is not established.
  - The detailed difference between the vortex ring state for a single helicopter rotor and side-by-side proprotors is not well understood.
  - The effects of dynamic flight maneuvers on the vortex ring state are not known.

- In the past year very limited vortex ring state analyses and small scale wind tunnel tests have been conducted.

  - Depending on flight test results, larger scale wind tunnel vortex ring state testing may be necessary and is advocated in support of the development of simulation models and increased flight control authority.

## FINDINGS

- The testing that has already been conducted is sufficient to conclude that vortex ring state does not prevent the V-22 from being safely and effectively utilized. The currently proposed rate-of-descent flight limits are considered very conservative, and the Panel believes they are operationally acceptable.

- The higher disk loading of the V-22 results in a higher rate-of-descent boundary for encountering the vortex ring state than in conventional helicopters.
- The testing conducted to date is not sufficient to completely establish the expanded operational limitations.
- A minimum altitude loss technique has not been explored. If recovery is initiated at the first signs of vortex ring state, altitude loss can be minimized.
- The extent of the dynamic maneuvering effect on the vortex ring state boundary must be determined by additional flight testing.
- The current display of rate-of-descent to the flight crew is not acceptable. The scaling of the display is too coarse to permit effective monitoring of sink rate during decelerating transitions, given current and potential flight envelope limits.
- The current airspeed sensing and display system may not provide the pilot with adequate situational awareness concerning entry into the vortex ring state flight regime.
- The possible need for a vortex ring state warning system is recognized.
- There is no evidence from wind tunnel or flight test data that proprotor stall is involved in the vortex ring phenomenon on tiltrotors (Appendix H).
- Increased roll control authority could potentially improve recovery from roll-off in the vortex ring state, and perhaps restrict the flight conditions in which roll-off would be encountered.

# RECOMMENDATIONS

## High Priority Recommendations

- Resume and complete flight testing in accordance with Test Request 64 (TR-64) without delay.
- Revise the display of rate-of-descent information to the flight crew. The scale should be usable by the crew for observing rate-of-descent flight restrictions.
- Expand TR-64 to include tests in the 40–60 knot range to more accurately determine the vortex ring state boundary.
- Conduct additional flight tests to determine the extent of the dynamic maneuvering effect on the vortex ring state boundary, if TR-64 is insufficient to do so.
- Use flight test results to modify current vehicle operational rate-of-descent flight restrictions, if required.
- Determine if a warning system is needed; if so, develop a system that will avoid frequent and obtrusive alarms.

- Once adequate flight test and any supporting wind tunnel data are available, incorporate a vortex ring state model into flight simulators for avoidance and recovery training.

## Vehicle Enhancement Recommendations

- Investigate increased roll control authority to provide greater vortex ring state margin and control of aircraft in the event of roll-off in high rate-of-descent flight.

- Evaluate the resulting flight envelope against V-22 mission requirements; consider envelope expansion.

# POWER-OFF (ALL ENGINES INOPERATIVE) AND AUTOROTATION



## DESCRIPTION

Upon loss of all power, tiltrotor aircraft can glide in airplane mode with proprotors wind-milling and can descend in helicopter mode autorotation. The descent rate of a V-22 in airplane mode is higher than that of a conventional airplane because of the wind-milling proprotors' drag. When a conventional airplane glides with all engines inoperative, the propellers are usually feathered and do not rotate.

The tiltrotor's descent rate in helicopter mode autorotation (typically 3,000-3,500 ft/min) is higher than that of helicopters (<2,800 ft/min). As a consequence of the tiltrotor's higher disk loading and lower proprotor inertia (high power requirement and small radius), the energy management task involved in an autorotative landing is more challenging than it is for a conventional helicopter.

## GOAL

Ensure safe one-engine-inoperative operation in all modes and survivable all-engines-inoperative landings in the airplane mode.

## KEY INFORMATION

For any multi-engine rotorcraft, including tiltrotor aircraft, consideration must be given to one engine inoperative and all engines inoperative conditions in all modes of operations.

- V-22 procedures require mission abort and landing as soon as possible after the failure of one engine. If an immediate landing is not possible, conversion to airplane mode is to be performed, with reconversion to helicopter mode only on final approach.

- Tiltrotor aircraft, including the V-22, have excellent potential for a survivable all-engines-inoperative landing in airplane mode.

- The V-22 specification SD 572-1 All Engines Failed Capability states: "If all engine power is lost at Structural Design Gross Weight at Sea Level-Standard conditions, it is desired that a safe landing envelope exist; it is required that an injury-free landing envelope exist. Power-off conversion from high speed flight (nacelles down) to low speed flight (nacelles up) shall be possible from anywhere within the 1g trimmed level flight envelope."

- Civil regulations, according to FAA Part 29.79(b) Landing; Category A engine isolation, state: "It must be possible to make a safe landing on a prepared landing surface if complete power failure occurs during normal cruise." Autorotation is not specifically required.

- There are at least two specific situations in which the V-22 may be required to autorotate:

    1) A dual engine failure while in conversion or in helicopter mode
    2) The loss of a single engine coupled with an interconnect drive train failure in conversion or in helicopter mode

- In terms of the aerodynamics of the proprotors, autorotation refers to equilibrium descent with zero power, either vertical or with forward speed. Tiltrotor aircraft can autorotate, but a full power-off landing may not be practical.

- For any transport rotorcraft, helicopter or tiltrotor, operating at low altitude and low airspeed, a survivable recovery is in doubt if multi-engine failure/all-engines-inoperative is experienced.

## FINDINGS

- Simultaneous independent loss of both engines is considered to be a very low probability.

- The capability of the V-22 to perform a survivable all-engines-inoperative landing in the helicopter mode has not been established.

- Tiltrotor aircraft, including the V-22, have excellent potential for a survivable all-engines-inoperative landing in airplane mode.

- A tiltrotor aircraft, as demonstrated with the XV-15, can sustain an autorotative glide. It can descend in helicopter mode in a controlled manner with no power to the proprotors. This also applies to the V-22.

There are possibilities of improving all-engines-inoperative airplane mode glide such as determining the auto-flap settings for best glide.

- Transport tiltrotor aircraft, because of energy management difficulties in an autorotative landing, may not be able to execute a survivable all-engines-inoperative landing in the helicopter mode.

# RECOMMENDATIONS

## High Priority Recommendations

- Conduct flight tests to develop one-engine-inoperative and height-velocity diagram databases.

- Perform simulation and additional flight tests, if required, to develop procedures that maximize the probability of achieving a safe landing in the one-engine-inoperative condition.

- Demonstrate in flight one-engine-inoperative conversion and reconversion.

- The ability to perform a personnel survivable all-engines-inoperative landing under all flight and weight conditions in helicopter mode should not be a mandatory program requirement. The Panel believes this requirement is not met by any transport helicopter in military use today.

## Vehicle Enhancement Recommendations

- Revised airplane mode one-engine-inoperative and all-engines-inoperative procedures and training should be developed. The V-22 requirements (specification SD 572-1) should be reviewed regarding power-off operation and revised to reflect the preferred airplane mode landing.

- The possibilities of improving all-engines-inoperative airplane mode glide (e.g., auto-flap settings for best glide) should be examined.

# SHIPBOARD COMPATIBILITY



## DESCRIPTION

Shipboard compatibility refers to the ability to operate the V-22 aboard ship. It includes the interaction between a ship's air wake and wave driven deck motion and the aircraft's aeromechanics. This generally involves low speed flight including takeoff, approach, and landing, and takeoff operations, as well as the aerodynamic and ship motion interactions while the aircraft is operating on deck. In the case of multiple aircraft shipboard operations, it can include the aerodynamic effects of one vehicle on another in the presence of ship's deck and superstructure.

Shipboard compatibility is evaluated through a process known as Dynamic Interface testing. Dynamic Interface tests (flight and landing tests conducted at sea, supported by simulation and wind tunnel tests) define operational restrictions for each ship/rotorcraft/Harrier combination for amphibious helicopter assault (LHA) and amphibious helicopter dock (LHD) class ships, including spot landing distinctions. The Dynamic Interface process is a proven Naval Air Systems Command method for developing an aircraft's shipboard operational envelope.

## GOAL

Enable robust shipboard operations with a minimum of restrictions.

## KEY INFORMATION

V-22 represents a new class of aircraft that will provide a new set of shipboard operational challenges as compared to previous aircraft. It is expected that operations of the V-22 will become more robust as the flight crews and deck crews become more familiar with its shipboard characteristics.

- During testing, a V-22 experienced an excessive roll response while operating on-deck with rotors turning. This was caused by another helicopter approaching for an upwind landing. This has led to a proposed restriction that the Panel believes is operationally unacceptable. The restriction would require that in high wind conditions, no aircraft could land less than 4 spots upwind of a V-22.

- Engineering analysis and potential solutions presented to the Panel give confidence that an understanding of the phenomenon is achievable, and that additional testing and development will lead to a solution that reduces or eliminates the need for such a restriction.

# FINDINGS

- V-22 Dynamic Interface tests have not been completed and data are limited.

- An excessive on-deck roll of a V-22, while operating on-deck with rotors turning, has resulted in a proposed limitation that the Panel believes is operationally unacceptable.

- Increased roll control authority may improve V-22 control response in the shipboard environment.

# RECOMMENDATIONS

## High Priority Recommendations

- Conduct further shipboard testing to expand the shipboard operations dynamic interface envelope.

- Conduct the engineering investigation, testing, and development needed to eliminate the requirement for a limitation on other aircraft landing at spots closely ahead of a V-22 with rotors turning. Include in the investigation possible stiffening of the V-22 landing gear system, increased roll authority, and other possible modifications to the flight control system that could improve overall shipboard handling.

# LOW SPEED FLIGHT/WIND AZIMUTH ENVELOPE



## DESCRIPTION

Critical azimuth refers to a flight/wind speed limitation established as a function of wind direction and aircraft heading. A rotorcraft should be capable of low speed flight in any direction, or of hovering in winds from any direction. The traditional helicopter requirement is 45 knot flight or winds in any direction, though this has not been achieved by all helicopters in the military inventory.

In evaluating low speed flight or operation in winds from various azimuths, aerodynamic interactions between the proprotor(s) and airframe can result in control requirements that cause critical azimuth wind restrictions**.**

## GOAL

Expand the wind-azimuth operational flight envelope to 45 knots in any direction.

## KEY INFORMATION

Flight envelope restrictions for flight at low speed or in winds from various directions have been established, based on limited flight tests to date. The Panel believes current Naval Air Training and Operating Procedures Standardization (NATOPS) restrictions are not operationally acceptable. These restrictions are a result of unique V-22 aerodynamic phenomena, which include pitch-up-with-sideslip, rearward flight, and sideward flight effects of the aircraft.

- Pitch-up-with-sideslip occurs when the upwind proprotor downwash impinges upon the rear empennage and causes the aircraft to pitch up. On the V-22 it is encountered in forward quartering winds (30 to 75 degrees relative to the nose of the aircraft) greater

than 20 knots. It sometimes requires full longitudinal stick and rapid forward nacelle positioning to recover.

- The basic phenomenon resulting in pitch-up-with-sideslip is understood, but the details of the aerodynamic interactions required for minimizing this effect have not been explored.
- Rearward flight (or hovering with a protracted tail wind) can produce a nose-up movement because of the aerodynamic impact of the horizontal tail.
- If rearward flight is attempted with cyclic alone, the longitudinal control margin can be depleted.

Future research: Wind tunnel testing may be used to investigate the aerodynamic phenomena associated with low-speed flight. These wind tunnel investigations can develop future aerodynamic modifications that might allow a further expansion of the flight envelope.

# FINDINGS

- Flight envelope restrictions for flight at low speed or in winds from various directions have been established, based on limited flight tests to date. The Panel believes current NATOPS restrictions are not acceptable.
- Although test aircraft have a relatively accurate low airspeed system and sideslip indicator, operational aircraft do not.
- Increased longitudinal control authority could have the potential to improve the pilot's ability to counter pitch-up-with-sideslip.

# RECOMMENDATIONS

## High Priority Recommendation

- Conduct additional flight tests of the V-22 operating in low speed flight around the azimuth to expand operational flight restrictions, and to investigate flight control procedural techniques including nacelle control.

## Vehicle Enhancement Recommendations

- If flight testing warrants, conduct a wind tunnel test to (1) investigate the aerodynamic phenomena of low speed flight regarding both critical azimuth issues and pitch-up-with-sideslip and (2) develop aerodynamic modifications that can allow an expansion of the flight envelope.
- Investigate increased longitudinal control authority, particularly with regard to minimizing pitch-up-with-sideslip.
- Conduct investigations to determine if an affordable low air speed and/or sideslip indicator can be developed for operational use.

# FORMATION FLIGHT AND AIR-TO-AIR REFUELING



## DESCRIPTION

The flight of any aircraft near, or in the wake of, another aircraft involves complex aerodynamic interactions. Situations of interest are formation flights involving V-22 aircraft, in the helicopter or conversion modes during takeoffs and landings, tactical maneuvering, cruise, and aerial refueling.

## GOAL

Establish a safe envelope for formation flying which will ensure safe separation during takeoffs, landings, and cruise formation flying. This should include aerial refueling operations.

## KEY INFORMATION

The current restriction on V-22 separation distances for formation flight (and landing zone separation) in helicopter mode is based on limited test data and on the standard practice for helicopter formation flying, which includes one helicopter flying in another helicopter's turbulent wake. The limits are based on roll excursions, apparently caused by lead aircraft wake aerodynamics, and by the apparent lack of roll control authority to maintain roll attitude.

- The unique capabilities of tiltrotor aircraft to make rapid changes in nacelle configuration, speed, and rate-of-descent differ significantly from those of other aircraft. These capabilities must be fully explored when developing formation flight and landing zone procedures.

# FINDINGS

- The V-22 wake characteristics and the adverse response characteristics of V-22 interactions to the wakes from other tiltrotors, helicopters, and fixed-wing aircraft are poorly characterized at present. More flight testing is required to define 'avoid areas' within the wakes of typical lead aircraft.

- Repeatable incidents of insufficient controllability have been observed during encounters with lead aircraft wakes during formation flights in conversion and helicopter modes.

- Airplane mode aerial refueling tests were completed successfully. However, in conversion mode, aerial refueling tests were unsuccessful because of pilot workload and apparently insufficient roll control when in the wake of the KC-130 tanker.

- V-22 formation flight in airplane mode has exhibited relatively stable flying qualities.

- Formation flight procedures, in helicopter and conversion mode, which minimize adverse lead aircraft wake interactions, have not been developed.

- Current separation distance restrictions and formation flight procedures are based on limited test data and influenced by the standard practice for helicopter formation flying.

- Planned flight tests TR-65 have not been completed.

# RECOMMENDATIONS

## High Priority Recommendations

- Conduct the planned flight-testing (TR-65) of two V-22s in formation flight, emphasizing typical mission maneuvers in helicopter and conversion mode. Extend these tests to include more than two V-22s (up to six, if practical).

- Develop operationally acceptable formation flight procedures and separation limits for takeoff, approach, landing, cruise, and aerial refueling.

## Vehicle Enhancement Recommendation

- Investigate the feasibility of flight control system enhancements to minimize objectionable aircraft response characteristics during interaction with lead aircraft air-wake.

# HOVER PERFORMANCE



## DESCRIPTION

The hover performance and efficiency of a tiltrotor depend on the combination of engine power availability and the aerodynamic behavior of each proprotor, acting in the presence of the wing, fuselage, nacelle, and the other proprotor. This includes the download on the wing and fuselage produced by the wake of each proprotor and the vertical thrust of the engine exhaust. Performance is also dependent on density altitude and propeller tip Mach number, both of which are functions of ambient temperature.

## GOAL

Define a flight-validated hover performance envelope over the entire operating temperature and altitude range with operational limits set accordingly.

## KEY INFORMATION

- Future Research and Development:
  - Future research should determine why the isolated single proprotor vertical performance data differs significantly from V-22 hover flight test results.
  - Since hover download reduction directly increases payload and range, hover download reduction research programs offer a high payoff.

## FINDINGS

- Based on the hover test results to date and on information provided, the V-22 will meet all mission requirements.
- Not all hover flight tests have been completed.

# RECOMMENDATIONS

## High Priority Recommendation

- Complete flight tests to define hover performance throughout the operating range of the aircraft, particularly at high altitude and in hot and cold weather environments.

## Vehicle Enhancement Recommendation

- Investigate why actual vehicle hover performance is different from that predicted based on isolated rotor tests.

# III. OTHER ISSUES

# FLIGHT CONTROL SYSTEM

## KEY INFORMATION

Instances of uncommanded aircraft movements as a result of the external aerodynamic environment have required the need for full control displacement to recover. This lack of control margin suggests that the aircraft may lack adequate control authority, particularly about the roll axis, but also about the pitch axis for the case of pitch-up with sideslip. However, piloting technique including the use of nacelle trim has not been fully investigated.

In the event that suitable handling qualities for all flight regimes is not found, additional flight tests, analyses and simulations should be conducted to determine the need for and benefits of increased control authority.

- As noted in earlier sections:
  - Vortex Ring State Finding: "Increased roll control authority could potentially improve recovery from roll-off in vortex ring state, and perhaps restrict the flight conditions in which roll-off would be encountered."
  - Vortex Ring State Recommendation: "Investigate increased roll control authority to provide greater vortex ring state margin and control of aircraft in the event of roll-off in high rate-of-descent flight."
  - Shipboard Compatibility Finding: "Increased roll control authority may improve V-22 control response in the shipboard environment."
  - Low Speed Flight / Wind Azimuth Finding: "Increased longitudinal control authority could potentially improve the pilot's ability to counter pitch-up-with-sideslip."
  - Low Speed Flight / Wind Azimuth Recommendation: "Investigate increased longitudinal control authority, particularly with regard to minimizing pitch-up-with-sideslip."
  - Formation Flight Recommendation: "Investigate the feasibility of flight control system enhancements to minimize objectionable aircraft response characteristics during interaction with lead aircraft air-wake."

## FINDINGS

- The interaction between the pilot and the flight control system are factors in the vortex ring state, Shipboard Compatibility, Low Speed Flight, and Formation Flight aeromechanical phenomena.
- Modifications to the flight control system could assist recovery from roll-off in the vortex ring state region.

# RECOMMENDATION

## Vehicle Enhancement Recommendation

- Investigate modifications of the flight control system to increase control authority with emphasis on authority about the roll axis. Special attention should be given to the difficult flight conditions experienced in shipboard operations, low speed flight, and formation flight.

# COMMUNICATIONS: DEFICIENCY REPORTING PROCESS

## KEY INFORMATION

A lateral Pilot Induced Oscillation (PIO) problem aboard USS SAIPAN was handled and resolved by the Integrated Test Team, NAVAIR and the contractors, in an expeditious manner. In contrast to that process, the handling of the engineering and risk assessment of the on-deck dynamic roll anomaly, cited in the Shipboard Compatibility section of this report, involved a significant delay.

## FINDINGS

- The severity of deficiency must be promptly noted so that appropriate organizations, such as the top engineering level and personnel can immediately address the problem, as was done in the PIO case.

- Appropriate classification of the severity of the deficiency is critical. Part I deficiencies appear to get immediate visibility and attention. Part II and III deficiencies may not get immediate attention, and thereby delay the remediation effort. This delay is acceptable and may even be desirable for minor issues, but it could be serious if a significant event is inappropriately under-classified.

## RECOMMENDATION

### Vehicle Enhancement Recommendation

- Review the Deficiency Reporting Process and require expert independent deficiency classification (Part I, II, and III) in a timely manner.

# IV. APPENDIXES

# APPENDIX A - U.S. NAVY REQUEST LETTER

DEPARTMENT OF THE NAVY
NAVAL AIR SYSTEMS COMMAND
RADM WILLIAM A. MOFFETT BUILDING
47123 BUSE ROAD, BLDG 2272
PATUXENT RIVER, MARYLAND 20670-1547

13150
Air-00
24 May 01

Dr. Henry McDonald
Director, Ames Research Center
M/S 200-1
National Aeronautics and Space Administration
Moffett Field, CA 94035-1000

Dear Dr. McDonald:

I am certain you are aware of the recent Department of Defense Blue Ribbon Panel's evaluation of the V-22 Osprey. As a result of the Panel's findings, the Navy has decided to conduct an independent assessment of Tiltrotor aeromechanics - focusing on 'vortex ring' characteristics and autorotation. We are interested in addressing the complete spectrum of topics - from theory and experiments through full-scale testing, with contributions from academia, government, and industry. I would expect a report in about mid-July, followed by presentations to senior leadership in both the Navy and Defense Department.

Given NASA's long history in Tiltrotor research, I believe it would be appropriate for NASA to lead such an assessment and seek your concurrence.

Mr. John McKeown is my coordinator and had some informal discussions with Dr. John Zuk regarding your potential assistance. You may reach Mr. McKeown at (301)342-4091 or by email, mckeownjo@navair.navy.mil.

Thank you for your consideration.

Sincerely,

J. A. COOK
Rear Admiral, U.S. Navy

# APPENDIX B - PANEL MEMBERS

- Chair: Dr. Henry McDonald
  - Director, NASA Ames Research Center
  - National Academy of Engineering (NAE) member
- Bruce Blake
  - Retired Boeing Director of Research and Technology
- Eric Bries
  - FAA Rotorcraft Directorate Assistant Manager
  - Naval Test Pilot School graduate
  - FAA test pilot
- Dr. Richard M. Carlson
  - Retired Director of the Army Aviation Research & Technology Activity
  - Retired Lockheed Director of Technology
  - NAE member
- Charles Crawford
  - Powered Lift Systems Team Leader, Georgia Institute of Technology Research Institute
  - Retired Army civilian (Qualified UH-60 and AH-64)
- Daniel C. Dugan
  - NASA Ames research engineer
  - Naval Test Pilot School graduate
  - XV-15 pilot
- Sandra Hart
  - NASA Ames human factors researcher
- Franklin D. Harris
  - Active consultant
  - Retired Bell vice president
- Robert Lynn
  - Active consultant
  - Retired senior vice president of Research and Engineering, Bell Helicopter Textron
- Dr. Robert Loewy
  - Chairman, School of Aerospace Engineering, Georgia Institute of Technology
  - NAE member
- Dr. W. James McCroskey
  - NAE Member
  - Retired Army civilian rotorcraft researcher
- Lt. Col. John Rudzis, USMC, retired
  - Delta Airlines pilot
  - Former V-22 Integrated Test Team director

Naval Test Pilot School graduate

- Dr. E. Roberts Wood

  Professor and former Aeronautics and Astronautics Department Chairman, Naval Postgraduate School

  Retired manager of Aeromechanics, McDonnell Douglas

## Biography
## Dr. Henry McDonald

Dr. Henry McDonald was appointed director of NASA Ames Research Center, Moffett Field, California, by NASA Administrator Daniel S. Goldin on 19 January 1996. McDonald officially assumed his new responsibilities on 4 March 1996.

Previously, McDonald was the assistant director of computational sciences and professor of mechanical engineering at the Applied Research Laboratory, Pennsylvania State University. He is currently on loan to NASA through the Mississippi State University where he holds a position as professor of engineering.

McDonald was born on 24 January 1937, in Glasgow, Scotland. He earned a bachelor's degree in aeronautical engineering with honors and a doctorate in engineering from the University of Glasgow. In 1992, he was appointed a Fellow of the American Society of Mechanical Engineers. In 1996, he was appointed a Fellow of the Royal Aeronautical Society. In 1997, Dr. McDonald had conferred upon him the Honorary Degree of Doctor of Engineering by the University of Glasgow, Scotland. In 2000 he was elected to membership in the National Academy of Engineering. He was awarded the NASA Outstanding Leadership Medal in 1999 and in June of 2000 was awarded the NASA Distinguished Service Medal.

McDonald has authored many papers on aeronautical research and development, has been a member of several aeronautical associations, and has served on several advisory panels for the federal government. He is an accomplished pilot, having been trained in the Royal Air Force Reserve, and is a sailing enthusiast. McDonald and his wife, June McDonald, M.D., are naturalized U.S. citizens and they have three children.

# APPENDIX C - TECHNICAL TEAM MEMBERS

**NASA Ames Research Center**

- Dr. John Zuk, executive secretary
- Mark Betzina
- Robert Callaway
- Dr. Frank Caradonna (Ames/Army civilian)
- William A. Decker
- Dr. Wayne Johnson
- Lt. Comdr. Glen Knaust, U.S. Navy
- Kurt Long, U.S. Navy
- Megan McCluer
- Dr. Wayne Mantay (NASA Langley Research Center/Army civilian)

**Bell Helicopters Textron**

- Tom Wood
- Troy M. Gaffey
- Richard F. Spivey

**Boeing Company**

- Michael A. McVeigh
- Leon A. Zmroczek

**V- 22 Integrated Test Team**

- Ray Dagenhart, NAVAIR
- Tom Macdonald, Boeing test pilot

**Air Force CV-22**

- Steve Connelly, HQ AFSOC PM Office
- Lt. Col. Tom Currie Jr., USAF, CV-22 Government Flight Test Director

**NAVAIR 4.3**

- Jerry Weakley
- Mark Silva

**HMX-1**

- Maj. Anthony Bianca, USMC, MV-22 Flight Test Director
- Maj. Chris Seymour, USMC, CV-22 test pilot

**Advisors**

- Dr. Jack Franklin, NASA Ames
- Martin Maisel, Ames/Army civilian
- Dr. Robert Ormiston, Ames/Army civilian
- John McKeown, NAVAIR

# APPENDIX D - AEROMECHANICAL PHENOMENA QUESTIONS

## General Tiltrotor Questions

- What are the aeromechanics phenomena (such as vortex ring, autorotation, low speed maneuvering, etc.) that could be encountered by tiltrotor aircraft?
- What are the aeromechanics and operational considerations regarding these phenomena (include both military and civil transport and utility missions, as well as the Special Forces mission)?
- How have these phenomena been investigated, evaluated, and validated? What is our basic understanding of the phenomena and what analysis, wind tunnel testing, simulation, and flight testing have been accomplished to improve our understanding?
- As a summary and guide for the future, regarding both phenomena and methods, what do we not know that we need to know about tiltrotor aeromechanics?

## Dr. McDonald's Questions Pertaining to V-22

- How is the vehicle design flight envelope defined by aeromechanics issues?
- How well has this flight envelope been validated in a) flight test, b) wind tunnel tests, and c) analysis? Have there been any surprises?
- What emergencies have been considered as part of the design process?
- What procedures have been developed to handle these emergencies?
- To what extent and how have these procedures been evaluated?
- In the Panel's view, have the likeliest emergencies been considered?
- In the Panel's view, are the procedures that have been developed the best for these emergencies?
- More specifically, are the operational limits and procedures for high rate of sink flight appropriate?
- Is the loss of control (roll, pitch, etc.) in high rate of sink conditions as expected? Understood?
- In the Panel's opinion, have suitable procedures for regaining control, following encountering loss of control conditions, been developed? Demonstrated?
- In the Panels opinion, have such dangerous flight conditions been adequately mapped out?

# APPENDIX E - SCHEDULE

- May 24
  Written request from Rear Admiral Cook
- May 24 – June 10
  Formed Technical Team and Panel
- June 11
  Invited University presentations on relevant activities
- June 14, 15
  Full Technical Team meeting
- June 18, 19, 26
  Invited university presentations on relevant activities
- June 26, 27
  Second full Technical Team meeting
- June 28, 29
  First Panel meeting
- July 10
  Dr. McDonald briefs progress to V-22 Executive Program meeting (Videocon)
- July 19, 20
  Second Panel meeting
- August 8
  Dr. McDonald briefs progress to Deputy Undersecretary of the Navy, Paul Schiender
- August 13
  Dr. McDonald briefs progress to Secretary of the Air Force
- August 14
  Dr. McDonald briefs progress on vortex ring state and All Engines Inoperative to Under Secretary of Defense for Acquisition, Technology, and Logistics, Pete Aldridge
- August 18
  Dr. McDonald e-mails progress on other Aeromechanical Phenomena to Under Secretary of Defense for Acquisition, Technology, and Logistics, Pete Aldridge

# APPENDIX F - MEETING AGENDAS

**Tiltrotor Aeromechanics Independent Assessment**
**Panel Agenda**
**NASA Ames Research Center**
**June 28, 2001**

## Background

8:00 AM: Welcome / Panel Charge - Dr. McDonald

8:30: V-22 Blue Ribbon Report Aeromechanical Overview - Bryan O'Connor

9:00: V-22 Analysis for Director of Operational Test & Evaluation - Dr. Arthur Rivolo, IDA

9:30: V-22 Envelope, Procedures, & Emergencies – Troy Gaffey

10:00: V-22 Flight Testing Overview – Tom Macdonald

10:15: Break

## Aeromechanical Phenomena

10:30: Overview / Process - J. Zuk

- Tech Team Reviewed Presentations:
- Aeromechanical Phenomena Matrix

11:00: Vortex Ring State - Mark Betzina & Frank Caradonna

**12:00: PM: Lunch**

1:00: Vortex Ring State Continued

2:00: Autorotation / Poweroff - Tom Wood (Bell) & Tom Macdonald, ITT (Boeing)

- One Engine Inoperative + Interconnect Failure

3:30: Break

3:45: Shipboard Compatibility - Kurt Long

- On Deck
- Interactional Aero (shipboard)
- Interaction with aircraft

5:00: Critical Azimuth - Tom Macdonald

- Pitchup with sideslip
- Rearward flight
- Power requirement issues

5:30: Adjourn

Note: All reports and discussions are to be considered pre-decisional/deliberative material. Please do not discuss the deliberations with people outside of the Technical Team/Panel members

**Tiltrotor Aeromechanics Independent Assessment**
**Panel Agenda**
**NASA Ames Research Center**
**June 29, 2001**

**Aeromechanical Phenomena Continued**

8:00: AM: Formation Flight - Bill Decker

- In-trail
  - Refueling with C-130 (conversion mode – helicopter drogue)
  - Other aircraft (V-22 & V-22, V-22 & Helicopter)
  - Landing Zone

8:30: Pitch Departure Characteristics- Mark Silva

9:00: Hover-in-ground effects - Bill Decker

9:30: Rotor Stall - Wayne Johnson

10:00: Break

10:15: Hover Performance - Tony McVeigh

10:45: Matrix Summary / Discussion – Wayne Johnson

12:00 PM: Lunch

**V-22 Specific Questions**

1:00: V-22 Low Airspeed / High-Rate-of-Descent Operational Limits & Emergency Procedures

1:30: Specific Responses to V-22 questions not addressed

- ITT, NAVAIR, Bell Boeing, HMX-1, CV-22

Panel Deliberations

2:00: Panel Deliberations – Dr. McDonald & Panel

3:00: Break

3:15: Panel Deliberations Continued

4:00: Action Items / Assignments? Next meeting Date – Dr. McDonald & John Zuk

4:30: Adjourn

Note: All reports and discussions are to be considered pre-decisional/deliberative material. Please do not discuss the deliberations with people outside of the Technical Team/Panel members

**Tiltrotor Aeromechanics Independent Assessment**

# Second Panel Meeting Agenda
# NASA Ames Research Center
**Bldg 210, Room 115**
# July 19, 2001

## Additional Information

8:00 AM: Welcome / Update / Meeting Objectives - Dr. McDonald

8:30: TR-64, TR-65 & Other Flight Test Overview – Ray Dagenhart

9:00: Operation Evaluation - Shipboard Operations – Major Bianca

9:30: V-22 Lateral Pilot Induced Oscillation Mitigation – John McKeown

9:45: Break

10:00: V-22 Control Authority – Bell Boeing

1) Lateral Control Power
2) Analysis of Roll Events on Deck

11:00: Marana Accident and V-22 Flight Control System Factors – John Rudzis

11:15: Updates: Low Speed Air Data Systems: Flight Test & Operational Candidates, Potential Warning Devices, Powered W. T. models, etc. - TBD

11:30: Lunch – Free, in front of Bldg 200

**Findings / Recommendations**

12:30 PM: Short Haul Civil Tiltrotor VMS Tour – Bldg 243

1:00: Panel Issues / Findings Priorities

1:30: Findings & Recommendations Discussions

3:15: Break

3:30: Findings & Recommendations Discussions Continued

5:00: Small Scale V-22 / Wind Tunnel Test Demonstration - Bldg 260

5:30: Adjourn

Note: All reports and discussions are to be considered pre-decisional/deliberative material. Please do not discuss the deliberations with people outside of the Technical Team/Panel members

**Tiltrotor Aeromechanics Independent Assessment**
**Draft Second Panel Meeting Agenda**
**NASA Ames Research Center**
**Bldg 210, Room 115**
**July 20, 2001**

8:00 AM: Findings & Recommendations Discussions Continued

10:00: Break

10:15: Findings & Recommendations Discussions Continued

12:00 PM: Lunch

1:00: Summary Discussions

2:30: Report Review Plans – Dr. McDonald

3:00: Adjourn Meeting

3:15: Vortex Ring State Tiltrotor Model Demo in Wind Tunnel - 7X10 – Bldg 215

Note: All reports and discussions are to be considered pre-decisional/deliberative material. Please do not discuss the deliberations with people outside of the Technical Team/Panel members

# APPENDIX G - INVITED PRESENTATIONS

- OSD/Director of Operational Test & Evaluation
  - Arthur Rivolo, Institute of Defense Analysis (IDA). Presented pertinent highlights of the findings of the report "Combined Operational Test and Evaluation and Live Fire Test and Evaluation Report on the V-22 Osprey," conducted for the Director of Operational Test & Evaluation Office for the Secretary of Defense.
- University of Maryland
  - Professor Gordon Leishman. Using a simple "Autorotative Index," compared tiltrotor with helicopter. Described in-depth vortex ring theory and presented helicopter experimental data. An eigenanalysis indicated that instability of two side-by-side rotor wakes occurred earlier than with a single isolated rotor.
- Naval Postgraduate School
  - Dr. Russel Duren. Discussed the use of a ground proximity warning system as a pattern to build a vortex ring state warning system. Demonstrated a vortex ring state warning system.
  - CDR Mark Couch. vortex ring state briefing highlighted a review of H-34 test data from a 1964 flight test, the associated high air-load fluctuations, a "pilot's perspective" of cockpit cues, and the ways a pilot can get into the vortex ring state.
- Pennsylvania State University
  - Dr. Ed Smith. Presented a vortex ring state literature review and reviewed the ongoing tiltrotor research at Pennsylvania State University.
  - Dr. Barnes McCormick. Reviewed aerodynamic theory and characteristics of a vortex ring state. Recommendations included an audio vortex ring state device similar to fixed-wing stall warning device.
- Georgia Institute of Technology
  - Dr. Lakshmi Sankar. Tiltrotor theoretical flow solutions from a range of codes, including TURNS and OVERFLOW, which are full Navier-Stokes CFD solutions. No specific solutions for vortex ring state were shown. Importance of the Institute's experimental capability presented.
  - Dr. JVR Prasad. Future vortex ring state research ideas
- Mississippi State University
  - Dr. David Whitfield. Full tiltrotor CFD solution using an unstructured-grid Navier-Stokes solver. Solutions used about 7 million grid points.
  - Dr. Robert King. Future vortex ring state research ideas. Iowa State University of Science and Technology
- Iowa State University
  - Dr. Ganesh Rajagopalan. Used ROT3DC, time-averaged lifting line, blade-element loading (a relatively low-resolution, incompressible Navier-Stokes equation solver with a simplified rotor representation). Over 30 solutions were presented that had been run over a 2-week period, to support the present vortex ring state problem.
- Continuum Dynamics
  - Dr. Todd Quackenbush and Dan Wachspress. Tiltrotor vortex ring CFD solution using a hierarchical free-vortex method, CHARM (includes a fuselage representation).

# APPENDIX H - ROTOR STALL AND VORTEX RING STATE IN TILTROTOR VEHICLES

During the initial consideration of vortex ring state aerodynamics of tiltrotors, following the loss of the V-22, the possibility that rotor stall was a factor in the phenomenon was considered. Based on wind tunnel tests and flight tests of the vortex ring state conducted since that event, and based on other test results, it is concluded that rotor stall is not a significant factor in the vortex ring state behavior of tiltrotors.

Concerns about stalling of tiltrotor blades in conditions other than very high thrust arises because of the large twist of tiltrotor blades. The twist is about 45 degree washout from center of rotation to tip. A helicopter rotor blade will have perhaps 10 or 15 degree washout. A tiltrotor blade is designed with large twist because it must operate efficiently as a propeller as well as a helicopter rotor. The 45 degree washout is larger than ideal for a hovering helicopter, but smaller than ideal for a high speed propeller.

The large twist of a tiltrotor blade leads to large geometric angles of attack at the blade root during operation in helicopter mode: that is, during hover, forward flight (edgewise flight of the rotor), and descent including autorotation and vortex ring state operation. The angles of attack are well beyond two-dimensional stall angles at the root. Yet when definitive hover measurements of the XV-15, Advanced Technology Blades (ATB), and Joint Vertical Experimental (JVX) tiltrotors were made at Ames Research Center, it was found that the performance was much better than anticipated based on conventional helicopter prediction methods, which accounted for root stall.

Now it is recognized that the three-dimensional flow at the root of the hovering tiltrotor blade allows much larger lifts than on a two-dimensional airfoil. The phenomenon can be characterized as radial flow or as centrifugal acceleration effects on the boundary layer, although that is too simple a picture of three-dimensional stall. Such effects have also been observed on propellers, and are central to the performance of stall-regulated wind turbines. So the existence of the phenomenon, and its importance for tiltrotor performance, are accepted. Methods have been developed to account for the phenomenon in tiltrotor design, although first-principles prediction using computational fluid dynamics codes is still in the future.

Wind-tunnel tests of a model tiltrotor in helicopter mode forward flight have shown measured performance that is still much better than conventional helicopter methods would predict, unless the effect of the stall delay is included. Wind tunnel test data that include tiltrotors in autorotation are also available. Thus the stall delay phenomenon survives the once-per-revolution and higher frequency variation of the aerodynamic environment on the rotor blade. So it is reasonable to expect that the stall delay will also persist in the low frequency, unsteady environment of the vortex ring state.

Since the loss of the V-22, both wind tunnel tests and flight tests have been conducted with the tiltrotor in the vortex ring state. In the wind tunnel, the test can be conducted by varying speed and shaft angle at fixed collective, so again rotor torque data can be examined for signs of rotor stall. The wind tunnel data do not suggest that rotor stall is important in the vortex ring state. At constant collective, a drop in lift as the angle of attack increases is an indication

of vortex ring state. This behavior occurs at both high and low thrust, so the lift change is produced by the rotor wake reducing the blade's angle of attack, not by blade's lift limits. Furthermore, at constant angle of attack, the rotor lift increases with collective, again indicating that the rotor lift limit has not been reached.

When the vortex ring state, including roll-off behavior, is encountered in flight, the power is, of course, low and the vibration high, so power and vibration can not be used to assess stall. In the vortex ring state, the load factor still increases with collective, indicating that the rotor lift limit has not been reached. Moreover, rotor stall has an easily recognized influence on rotor structural loads, notably, chord bending and pitch link loads. Based on such structural dynamic measurements, there is no sign of rotor stall in the results of the V-22 flight tests in the vortex ring state.

Hence, based on wind tunnel tests and flight tests of tiltrotors in vortex ring state, and based on other test results, it is concluded that rotor stall is not a significant factor in the vortex ring state behavior of tiltrotors.

# APPENDIX I – STATEMENT OF MR. BRIES

Mr. Bries concurs with the general recommendations stated in the text of the Executive Summary and the list of "High Priority Recommendations," also presented in the Executive Summary. However, he believes that the report generally overstates issues, especially in the vortex ring state and flight control systems sections. He is particularly concerned with the "Vehicle Enhancement Recommendations" on flight control system changes. In his view most of these items have straightforward, satisfactory solutions in the form of procedural changes and piloting technique, which will be established during the course of remaining flight tests. Given the facts available to the panel and the amount of flight testing yet to be completed, he believes it inappropriate to create an impression that the present flight control design is deficient. Finally, Mr. Bries believes that a number of the subjects which are defined as "aeromechanics phenomena" in the report are in fact minor events that are typically encountered during the course of any aircraft development program. Elevating them to "phenomena" status gives them unwarranted attention.