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EVALUTION OF V-22 TILTROTOR HANDLING QUALITIES IN THE INSTRUMENT METEOROLOGICAL ENVIRONMENT

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Scott Bennett Trail
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ABSTRACT

The purpose of this thesis is to document the handling qualities of the V-22 tiltrotor aircraft in instrument metrological conditions (IMC) and recommend procedures for V-22 operations in IMC. This evaluation was conducted in the Patuxent River Naval Air Station, Maryland local flying area in accordance with Naval Aviation Systems Command test plan V22-TP-012/02. Test flights consisted of basic instrument maneuvers, en route instrument navigation, instrument approaches, and simulated single engine missed approaches. All maneuvers were conducted under day visual meteorological conditions. En route navigation and instrument approaches were also conducted under simulated IMC using a helmet-mounted hood, and actual IMC. Handling qualities were evaluated for nacelle angle configurations of airplane mode at 0^o nacelle, conversion mode nacelle angles of 30^o, 45^o, and 61^o nacelle, and vertical takeoff and land (VTOL) mode at 80^o nacelle. The handling qualities associated with nacelle angle transitions between airplane mode, VTOL mode, and intermediate nacelle angles were also evaluated. The author participated in this test as a test pilot, basic instrument maneuvers, en route instrument navigation, instrument approaches, and simulated single engine missed approaches.

The stability offered by the fly by wire flight control system resulted in favorable stability and handling qualities for constant nacelle configurations in IMC. The capability to change configuration between airplane mode and VTOL mode or an intermediate nacelle configuration greatly increased flexibility to meet the demands of heavy air traffic or adverse weather conditions during IMC operations. Challenges to handling qualities in the IMC environment included altitude deviations during large nacelle angle changes and the requirement of the pilot to change control strategy for different nacelle configurations.

The author concluded that each nacelle configuration had unique characteristics, which could be used to meet the demands of a given operating environment. While one nacelle configuration exhibited better handling qualities for instrument approaches, other nacelle settings were preferable to meet the demands of heavy air traffic, low ceilings, degraded visibility, and single engine emergencies. It was concluded the pilot should be given the flexibility to choose the best nacelle configuration to meet the demands of the prevailing flight conditions.

PREFACE

The author obtained most of the data contained in this thesis during flight test conducted by the V-22 Integrated Test Team based at Patuxent River NAS. The research, opinions, and conclusions presented in this thesis are solely those of the author and are not an official position of the United States Department of Defense, the Office of the Secretary of Defense, the United States Marine Corps, the United States Navy, the United States Air Force, or the V-22 Integrated Test Team.

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation/Symbol	Definition
^{o}	degree(s)
AFCS	Automatic Flight Control System
AFFTC	Air Force Flight Test Center
AGL	Above Ground Level
ATC	Air Traffic Control
CDI	Course Deviation Indicator
CLAWS	(flight) Control Laws
DCP	Differential Collective Pitch
DH	Decision Height
FADEC	Full Authority Digital Electronic Control
FAF	Final Approach Fix
FCC	Flight Control Computer
FLIR	Forward Looking Infrared
fpm	Feet per Minute
HSD	Horizontal Situation Display
HQR	Handling Qualities Rating
IAF	Initial Approach Fix
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
ITO	Instrument Take Off
ITT	Integrated Test Team
LDO	Lateral and Directional Oscillation
LOC	Localizer
LWINS	Light Weight Inertial Navigation System
MAGR	Miniature Airborne Global Positioning Receiver
MAP	Missed Approach Point
MDA	Minimum Decision Altitude
MFD	Multi-Function Display
NAS	Naval Air Station
NAVAIR	Naval Aviation Systems Command
NM	Nautical Miles
OM	Outer Marker
PAR	Precision Approach Radar
PFCS	Primary Flight Control System
PFD	Primary Flight Display
TACAN	Tactical Air Navigation System
TCL	Thrust Command Lever
TDZ	Touch Down Zone
VMC	Visual Meteorological Conditions
VOR	Very High Frequency Omni-Directional Range
VTOL	Vertical Takeoff and Land

CHAPTER I
INTRODUCTION

Background

Following a grounding period and major aircraft redesign, the instrument meteorological conditions (IMC) flight clearance for the V-22 had been revoked. To regain the capability to operate in IMC, the V-22 integrated test team (ITT) was tasked with conducting an evaluation of V-22 operations in IMC in accordance with Naval Air Systems Command (NAVAIR) test plan V22-TP-012/02. Earlier phases of IMC testing evaluated the maturity of the aircraft's hardware configuration, software configuration, and systems integration. The final phase of testing was IMC flight test. This thesis will focus on the handling qualities portion of the V-22 IMC flight test, which took place in the Patuxent River Naval Air Station (NAS) local flying area from March through May 2004. The author participated in this test as a test pilot, flying during all phases of the flight test portion of the IMC test.

Purpose

The purpose of this thesis is to document the handling qualities of the V-22 in IMC and make recommendations for IMC procedures in the V-22. Basic instrument maneuvers, instrument departures, en route procedures, approaches, and simulated single engine missed approaches were evaluated. Recommendations for the transition point to final approach configuration and final approach nacelle angle configuration were determined.

Aircraft Description

Airframe

The V-22 is a tiltrotor aircraft produced jointly by Bell Helicopter Textron and Boeing Defense and Space Group (Figure A.1, V-22 Schematic). The tiltrotor design combines the vertical takeoff and land (VTOL) capabilities of a helicopter with the speed, range, and service ceiling of a turbo-prop airplane. The aircraft is a twin engine, twin proprotor, high wing, twin tail design with retractable landing gear. The proprotor system and airframe are primarily constructed of lightweight composite materials. The proprotors are named as such because they must function as rotors when the aircraft is in VTOL mode and as propellers when the aircraft is in airplane mode. The wing has a 3.5^{o} dihedral and a 6^{o} forward sweep. The aircraft utilizes fly-by-wire flight control system, with mechanical linkages limited to the cockpit area (Preliminary NATOPS Flight Manual MV-22B Tiltrotor, May 2005).

The nacelles rotate about the wing from horizontal, or 0^{o} to 96.3^{o}, or 6.3^{o} aft of vertical, relative to the aircraft's longitudinal axis. Different nacelle angle configurations are divided into three different modes, VTOL mode, conversion mode, and airplane mode. VTOL mode is defined as nacelle angles from 96^o to 75^o. Conversion mode is defined as nacelle angles from 74^o to 1^o. Airplane mode is defined as nacelles horizontal or at 0^o.

Aircraft control is provided by the flight control system. The flight control system is a triple redundant fly-by-wire system made up of mechanical flight controls, three flight control computers (FCCs), and flight control actuators. A conventional, tail mounted rudder, elevator, and wing-mounted flaperons provide flight control in airplane mode. The flaperons may be set to automatically program as ailerons or be set to move about a lower flap angle to function simultaneously as flaps and ailerons. In VTOL mode, flight control is provided solely by proprotor swashplate tilt. In conversion mode, flight control is provided by a combination of swashplate tilt and wing and tail mounted flight control surfaces.

The proprotor system consists of two, three-bladed, 38 ft diameter, counter rotating proprotors mounted to the nacelles. The proprotors provide lift and flight control when the nacelles are at or near vertical in VTOL mode and thrust when the nacelles are in the horizontal position, or airplane mode. The proprotors are mounted to a proprotor hub, which provides for blade flapping, coning, and pitch change. The hub assembly is stiff-in-plane with no lead-lag motion. The hub is all composite construction with elastomeric bearings, which dampen proprotor flapping, feathering angles, and proprotor loads. Control of tip-path plane tilt is achieved using the swashplate assembly. The swashplate assembly moves in response to flight control inputs, moving on a mast-mounted gimbal ring to achieve the desired proprotor pitch and tip-path-plane tilt angle.

Two 6,150-shaft horsepower Rolls Royce T406-AD-400/AE1007C engines, one mounted in each nacelle, power the proprotor system. The drive train incorporates an interconnecting drive shaft enabling one engine to provide power to both proprotors in the event of an engine failure (Figure A.1). Each engine is controlled by a dual-redundant, full authority digital electronic control (FADEC). The FADECs control the engine by adjusting fuel flow and compressor variable geometry vane angle. The FADECs automatically protect against engine overspeed, over-temperature, and over-torque in addition to providing data, status information and fault information.

Flight Controls

Modern tiltrotors require stability and control augmentation (Calise 1998). To meet that requirement, the flight control system in the V-22 uses a triply redundant fly-by-wire system that incorporates three FCCs. The FCCs control the Primary Flight Control System (PFCS) and Automatic Flight Control System (AFCS). The PFCS provides basic aircraft control, thrust or power management, force feel, and trim control. The PFCS also provides input shaping to overcome aircraft inertia, improve response time constant in VTOL mode, and desensitize the aircraft to abrupt cyclic stick inputs in airplane mode. The AFCS provides full-time rate stabilization, and attitude stabilization. The flight control approach used in the V-22 begins with an input made to the flight controls. Force feel feedback from the flight controls to the pilot is provided via the PFCS. The input is sent to the digital FCCs, which feed the input through the flight control laws (CLAWS) before sending a signal via wire link to the flaperons, elevators, and rudders. Flight control inputs are also sent to the proprotor swashplates in VTOL mode, but phased out to zero as nacelle angle decreases to zero in airplane mode.

Cockpit Flight Controls. The aircraft is controlled from the cockpit by a center-mounted cyclic stick that controls pitch and roll, a thrust control lever (TCL) that controls thrust, and pedals that provide directional control. An illustration of the cockpit flight controls is shown in Figure A.2. A knurled knob mounted on the TCL, operated by the pilot's thumb, controls nacelle movement. The nacelle controller is spring loaded to the center and is a rate command control that provides a maximum of 8^{o} per second rate of nacelle movement. A closer view of the TCL and nacelle controller is shown in Figure A.3.

The tiltrotor poses a unique demand on the human operator since the control response changes as it converts from slow flight as a helicopter to forward flight in cruise configuration as an airplane (Calise 1998). Airplane mode flight path control is accomplished via the elevator, flaperon, and rudder surfaces. In VTOL mode vehicle control is accomplished by proprotor tip-path-plane control similar to conventional helicopters. Specifically by axis, pitch is controlled through longitudinal cyclic, lateral control is obtained through differential collective combined with lateral cyclic, and height control is via symmetric collective commands. Longitudinal cyclic commands a forward or aft tilt of the proprotor tip-path-plane resulting in fore and aft movement. Lateral cyclic tilts both proprotors equally and in the same direction laterally resulting in lateral translation. Differential collective pitch increases collective pitch on one proprotor greater than the other proprotor resulting in bank angle changes. Figure A.6 illustrates these control mechanisms as a function of flight mode.

Control in conversion mode is a mixture of both rotor and airplane surface forces and moments. During conversion from VTOL to airplane mode, rotor control due to pilot command is phased out as a function of nacelle angle. However, the elevator, flaperons, and rudders are actuated full time, full authority regardless of nacelle angle. Actuating these surfaces full time augments the rotor control power during high-speed VTOL flight modes (Goldstein and Dooley 1986). A more detailed discussion of V-22 flight control follows in the next paragraphs.

VTOL Flight Control. VTOL mode is defined as flight with nacelle angles from 96^{o} to 75^{o}. Longitudinal control in VTOL mode is obtained by a combination of nacelle angle and symmetric longitudinal swashplate tilt forward or aft. For small longitudinal inputs in a hover or for low speed maneuvers, the pilot makes an input to the cyclic stick which causes the swashplates to move equally and in the same direction to achieve forward or aft movement. Maximum longitudinal swashplate tilt is available from 96^{o} nacelle until approximately 75^{o} nacelle. As nacelles rotate forward past 75^{o}, longitudinal swashplate tilt available decreases by 10% at 61^{o} nacelle, before decreasing to zero in airplane mode. For large inputs such as departure from a hover, the pilot rotates the nacelles forward while using longitudinal cyclic to maintain a level nose attitude. Controlling airspeed with nacelle angle enables the pilot to stabilize over a wide range of airspeeds while maintaining a nose level pitch attitude.

Lateral control in VTOL mode is obtained by a combination of lateral cyclic or lateral swashplate gearing (LSG) and differential collective pitch (DCP). LSG provides side force, causing the aircraft to translate laterally. DCP creates a rolling moment by increasing the pitch on proprotor blades one side at a greater magnitude than pitch is increased on the opposite side proprotor. Maximum or nearly maximum DCP is available up to 60^o nacelle. However, DCP is also dependent on airspeed and mast torque. Increased mast torque decreases DCP available. DCP also decreases for airspeed greater than 40 knots to zero at 60 knots. LSG is progressively phased out to zero as the nacelle angle is advanced down from 80^o to 75^o. LSG is also dependent on airspeed decreasing from the maximum value for airspeeds below 40 knots to zero for airspeeds greater than 60 knots.

Directional control in VTOL mode is provided by differential swashplate tilt. Differential swashplate tilt enables the aircraft to yaw by tilting one swashplate forward and the other swashplate aft. This proprotor tip-path-plane movement creates a moment about the vertical axis enabling the aircraft to yaw or rotate in the horizontal plane. The phasing out of differential swashplate tilt is a function of both airspeed and nacelle angle. Maximum differential swashplate tilt is available for nacelle angles from 96^o to 80^o at airspeeds below 61 knots. Differential swashplate tilt is phased out as airspeeds increase above 61 knots or nacelles move forward past 80^o gradually phasing out to zero at 0^o nacelle for all airspeeds.

Vertical control in VTOL mode is similar to a conventional helicopter in that increased power demand from the pilot results in a collective increase in pitch on all proprotor blades. The V-22 uses the TCL to command power and collective changes in VTOL mode. A TCL input results in a throttle command and collective proprotor pitch change. The collective pitch is gradually phased out as nacelle angle decreases. Unlike a conventional tail rotor helicopter, counter torque is provided inherently by the counter rotation of the proprotors.

Conversion Mode Flight Control. Conversion mode is defined as nacelle angles 74^o to 1^o. In this mode, flight control is achieved by a combination of swashplate tilt, differential collective pitch, and the conventional airplane control surfaces. As airspeed increases the dynamic pressure over the surfaces of the flaperons, elevators, and rudders, increase and these conventional control surfaces become more effective. As nacelle angle decreases and airspeed increases, the flight control computers gradually phase out the proprotor swashplate tilt. No pilot action is required to control this transition, however, the phasing out of DCP, LSG, differential swashplate tilt, and collective pitch have independent schedules, all of which are non-linear. This phasing out process throughout conversion mode requires the pilot to change control strategy for altitude and airspeed control. As the nacelles rotate down in decreasing nacelle angles, the aircraft's response to TCL results in pitch change, altitude change and airspeed change while in VTOL mode a TCL input produces an uncoupled response in the vertical axis. This pitch response to TCL input in the conversion mode is referred to as pitch power coupling.

Airplane Mode Flight Control. Airplane mode is defined as nacelles at 0^o. In this mode, flight control is similar to conventional fixed wing aircraft. Remaining proprotor swashplate tilt available is phased out to zero at 0^o nacelle and as airspeed increases with downward nacelle rotation, dynamic pressure of the control surfaces enables the aircraft to be controlled entirely by the flaperons, elevators, and rudders. The collective pitch commanded by the TCL in VTOL mode is also phased out and the TCL commands only throttle in airplane mode. However, the PFCS does increase collective pitch on the proprotor blades as nacelle angle decreases to maintain the blades within their operating angle of attack range. The PFCS also reduces flaperon gearing as airspeed increases to prevent excessive control power and sensitivity at very high airspeeds. This control arrangement requires a change in the control strategy in that TCL movement controls airspeed vice altitude in VTOL mode and altitude is controlled by pitch in airplane mode and TCL movement in VTOL mode.

Instrument Navigation Equipment

The V-22 navigation equipment consists of two fully redundant mission computers, a tactical air navigation system (TACAN), very high frequency omni-directional range (VOR), instrument landing system (ILS), miniature airborne global positioning receiver (MAGR), and triple redundant light weight inertial navigation system (LWINS). TACAN, VOR, ILS, and MAGR guidance, in addition to a moving map, can be displayed on any of the four the multi-function displays (MFDs). The arrangement of the MFDs in the cockpit is shown in Figure A.2. Under normal operations, the MAGR corrects for drift of aircraft position caused by Shuler cycle LWINS drift. While the MAGR can provide waypoint guidance, as installed on the V-22, the MAGR is not certified for instrument flight rules (IFR) operations.

Flight Displays

The four cockpit mounted MFDs enabled the pilot to select between flight displays, navigation display, forward looking infrared (FLIR) image, system status pages, and a system interface page. Each MFD is independent, allowing the pilot to select the desired display regardless what other MFDs were showing. The displays used to provide pilot orientation during IMC tests are the primary flight display (PFD) selected from the flight display page, and the horizontal situation display (HSD) moving map with selected TACAN or VOR guidance from the navigation page.

The PFD provides a digital display of aircraft attitude, nacelle angle, performance parameters, velocity vector, heading, mast torque, VOR, TACAN, ILS and course deviation indicator (CDI) needles, distance measuring equipment (DME), flight director guidance and status, stall warning indicator for nacelle angles below 30^o and selected warning messages such as “stall” and “fire”. A color picture of the PFD is shown in Figure A.4. The HSD provides a compass rose, moving map, DME, and selectable VOR, TACAN, and CDI needles. A color picture of the HSD is shown in Figure A.5. A complete illustration of the PFD and HSD displays and symbols is presented on Figures A.7 and A.8.

Aircraft Limitations

The V-22 has several limitations that have a significant impact on handling qualities in the IMC environment. The FCCs provide automatic limitation of power, structural load limiting, and nacelle conversion protection. The aircraft also has landing gear and landing configuration limitations.

The FCCs via the FADECs limit mast torque to 100% without interim power, or 109% mast torque with interim power active with full forward TCL input. This relieves the pilot of the requirement to limit TCL application to maintain mast torque within limits. Power limiting also increases the life of the engines and protects the transmission from an over torque condition. In addition, the FCCs provide structural load limiting. Structural load limiting modifies the aircraft’s control response only for flight conditions where the potential for structural damage exists. The structural load limiting control laws protect the proprotor, drive train, and airframe against exceeding structural limits. Again this alleviates the requirement of the pilot to monitor load factor, protecting the aircraft against structural damage.

High speed flight in VTOL mode can result in high proprotor hub loads. The FCCs protect against these high loads using conversion protection. Conversion protection is required to protect the rotor system from excessive flapping caused by blowback. Previous rotary wing designs accounted for rotor flapping with underslung mounted rotor heads or hinges in fully articulated systems. The V-22 does not use an underslung or fully articulated rotor system, but a stiff-in-plane rotor system because of the requirement for the proprotors to function both as rotors and propellers. Excessive flapping is of increased concern in modern rigid or stiff-in-plane rotor systems, such as those on the V-22, or BO-105, and Lynx helicopters, because flapping is dampened in these systems by plastic deformation of rotor head components and elastomeric bearings. To protect against excess flapping, conversion protection causes the nacelles to automatically program forward toward airplane mode as airspeed reaches the maximum allowable structural limit for a given nacelle angle. Additionally, the nacelles cannot be moved back toward VTOL mode if airspeed exceeds the conversion protection maximum value for the given nacelle angle (Preliminary NATOPS Flight Manual MV-22B Tiltrotor, May 2005).

The V-22 also has limitations for landing gear extension and retraction, minimum nacelle angle, and maximum landing speed. Extension, retraction, and flight with the landing gear extended are limited to 140 knots and below. Landing nacelle angle is limited to a minimum of 75^{o} for a roll-on landing because of limited lateral control at lower nacelle settings at low speeds. The maximum landing speed is limited to 100 knots ground speed because the landing gear has not been demonstrated beyond that speed.

CHAPTER II
METHOD OF TEST

Test Procedures

The IMC handling qualities flight testing consisted of three phases. The first phase was basic instrument maneuvers under day VMC with the pilot at the controls wearing an instrument hood. The second phase was instrument navigation and approaches area under day VMC with the pilot at the controls wearing an instrument hood. The third and final phase was instrument navigation and instrument approaches under day IMC. The results of each phase of test were reviewed before proceeding to the next phase. All flights were conducted in the NAS Patuxent River local flying area or nearby regional airports. The author was one of five test pilots who performed the IMC handling qualities evaluation. The author is the lesser-experienced pilot mentioned later in the text, as this was his first project as a V-22 test pilot.

Constant speed basic instrument maneuvers and unusual attitude recoveries were conducted in five different nacelle and airspeed configurations:

- 0^o nacelle at 200 knots
- 30^o nacelle at 150 knots
- 45^o nacelle at 130 knots
- 61^o nacelle at 110 knots
- 75^o nacelle at 80 knots

Instrument approaches were not conducted in airplane mode at 0^o nacelle, but were evaluated for the other four nacelle and airspeed configurations listed above. Airplane mode instrument approaches were not conducted because reconfiguring the aircraft from airplane mode to the landing configuration and landing within the touch down zone (TDZ) under low ceilings or visibility was not practical.

Basic instrument maneuvers included accelerations and decelerations, turns, climbs and descents. Turns, climbs and descents were also combined with accelerations and decelerations. A complete list and abbreviated description of each maneuver is contained on Table A.1.

En route procedures included instrument navigation and holding. The instrument approach portion of the test included precision approach radar (PAR), ILS, VOR, and TACAN approaches. Additionally simulated single engine approaches and lateral offset approaches were conducted under day, VMC, under a hood only. A complete list and abbreviated description of each maneuver is contained on Table A.4.

Data Gathering

The primary source of data for this test was pilot comments. For basic instrument maneuvers, the pilot assigned a handling qualities rating (HQR) to each task in accordance with the Cooper Harper Rating Scale shown on Figure A.11. The HQR scale is based on the pilot's assessment associated with a discrete task such as airspeed capture or altitude maintenance. Each task has defined desired and adequate tolerances within which the task must be performed. Desired and adequate tolerances for basic instrument maneuvers are included on Table A.3. Because instrument navigation and approaches encompassed a wide variety of tasks and tolerances, the Air Force Flight Test Center (AFFTC) descriptor evaluation scale was used. This scale enabled an assessment of the broad range of tasks and handling qualities associated with instrument approaches. The scale is shown on Table A.4 and had three ratings, satisfactory, marginal, and unsatisfactory. Desired and adequate tolerances for instrument navigation and approaches are contained in Table A.5.

For HQRs of 3 or lower or an AFFTC rating of satisfactory, only one pilot evaluation was required. For HQRs of 4 or higher or AFFTC ratings of marginal or unsatisfactory, a second pilot evaluated the maneuver. Some test aircraft flown during the evaluation were fitted with a 1553 data bus recording system that collected control position, FCC inputs, airspeed, altitude, heading, rate of climb or descent, and engine performance parameters. The data collected from the data bus recorder was consistent with the pilot comments and will not be included in this thesis.

Aircraft Configuration

No specific gross weights or centers of gravity were targeted for this test. Aircraft were flown with full fuel and without ballast resulting in a gross weight range of approximately 36,000 lb to 44,000 lb and a center of gravity near the center of the envelope. All V-22 ITT aircraft could be flown during this test including engineering manufacturing development, low rate initial production, and production aircraft. All of these aircraft were configured with one of the two most recent engineering development flight control software versions. These engineering software versions were intended for developmental use only and not intended for operational release but were considered operationally representative for the purposes of this test. All maneuvers were flown within the normal operating envelope of the aircraft. However, at the time of the test, operational flight in IMC was prohibited unless flown under NAVAIR Test Plan No. V22-TP-012/02, which governed the conduct of this test.

CHAPTER III
RESULTS

Basic Instrument Maneuvers

Basic instrument maneuvers described in the previous section were conducted using a helmet mounted instrument hood under day VMC. Basic instrument maneuvers were evaluated as a building block towards evaluating handling qualities during IMC navigation and approaches. Each basic instrument maneuver corresponded to individual flight tasks, which, when used together would be used during IMC navigation and approaches. For example, level accelerations and decelerations would be required when entering and leaving holding, and constant speed climbs and descents corresponded to en route altitude changes or descents during an instrument approach. HQRs were assigned to each maneuver according to the task tolerances listed in Table A.1.

For purposes of convention in this thesis, reduction in nacelle angle or changes in nacelle angle from VTOL mode to airplane mode will be referred to as transitions. Increasing nacelle angle from airplane mode to VTOL mode will be referred to as conversions.

Level Acceleration and Deceleration

<u>*Level Acceleration.*</u>

Procedure:

1. Perform level transition from 75^{o} nacelle and 80 knots, to 0^{o} nacelle (airplane mode) and 200 knots, targeting a slow to moderate nacelle rate.
2. Capture 200 knots and stabilize.
3. Complete task within 90 seconds.

The acceleration was completed in 55 seconds corresponding to a nacelle rate of approximately 1.3 ^{o}/sec. As the aircraft accelerated with the downward rotation of the nacelles, increasing aft cyclic stick force was required to prevent the nose from pitching down and losing altitude. Further increased aft cyclic stick was required as the nacelle angle passed through 30^{o}, as pitch attitude required to maintain altitude increased from nose level to 10^{o} nose up. Final pitch attitude was 7^{o} nose up at the final airspeed of 200 knots. TCL inputs were small during the acceleration. However, to capture the desired airspeed, three TCL movements corresponding to ± 30% mast torque were required as the aircraft accelerated rapidly through 200 knots. The targeted airspeed of 200 knots was near the minimum required airspeed of 180 knots. Airspeed was captured within 3 knots, heading maintained within ± 2^{o} and altitude was maintained within 20 ft using the altitude flight director. An HQR of 3 was assigned to the task for final airspeed capture.

Level Deceleration.

Procedure:

1. From stabilized flight, 0^{o} nacelle and 200 knots, initiate level deceleration using aft TCL.
2. At approximately 165 knots, initiate conversion with a slow to moderate nacelle rate.
3. Capture 75^{o} nacelle and 80 knots and stabilize.
4. Complete task within 90 seconds.

During the conversion to VTOL mode, nacelle rate was slight faster than 1 ^{o}/sec. As the nacelles rotated up, forward cyclic stick was required to maintain pitch and prevent altitude loss. As the nacelles rotated through 30^{o}, a significant increase in forward cyclic stick was required to move the nose to the horizon and allow the nacelles to control the deceleration while TCL controlled altitude with a level nose attitude. As the aircraft decelerated below 100 knots, a lateral and directional oscillation (LDO) was evident requiring lateral cyclic stick and pedal inputs to maintain desired heading. The task was completed in 69 seconds. Heading was maintained within 4^{o}, altitude within +20 ft and –10 ft and airspeed was captured within one knot using nacelles to control airspeed with a level pitch attitude. An HQR of 3 was assigned to the task of heading maintenance and workload required to dampen the LDO.

Level Turns

Procedure:

1. From level flight, roll to the standard rate turn in 3 seconds.
2. Maintain angle of bank for 180 degree heading change.
3. Capture the reciprocal heading, returning wings to level in 3 seconds.

0^{o} nacelle, 200 knots. Aircraft response to pilot inputs was similar to conventional airplanes with TCL functioning similar to a power control lever for controlling speed and longitudinal cyclic stick controlling altitude. Airspeed was maintained within 2 knots, heading was captured within 3 degrees and altitude was maintained within 30 ft. Pilot workload was low and an HQR of 2 was assigned to the task.

30^{o} nacelle, 150 knots. Control strategy was the same as 0^{o} nacelle and response to pilot inputs was predictable. However, unlike 0^{o} nacelle, there was a noticeable vibration at the 30^{o} nacelle configuration. The vibration did not adversely affect handling qualities. The aircraft climbed slightly during rollout, deviating 30 ft from desired altitude. Airspeed was maintained with 2 knots and heading was captured within 2 degrees. As the workload was similar to the 0^{o} nacelle level turn, an HQR of 2 was assigned to the task.

45° nacelle, 130 knots. Aircraft response at 45° nacelle was coupled in the pitch and power channels. The vibration evident at 30° nacelle was increased, but still had no noticeable effect on handling qualities. Aircraft response to a TCL or longitudinal cyclic stick input was a coupled response in altitude and airspeed. This required a coordinated and simultaneous use of TCL and longitudinal cyclic to correct for airspeed or altitude deviations. As a result of the coupled response, airspeed deviated from –2 knots to + 4 knots and altitude fluctuated from –20 ft to +60. Airspeed maintenance was the most difficult task due to the aircraft's coupled response. The HQR assigned was a strong function of pilot experience. A pilot with 19 hours flying the V-22 asigned an HQR 5, while a pilot with 200 hours flying the aircraft assigned an HQR of 3 to this task.

61° nacelle, 110 knots. Control strategy at 61° nacelle was similar to conventional helicopters with TCL functioning similar to a collective for controlling altitude and airspeed primarily controlled with nacelle using longitudinal cyclic stick for small airspeed corrections. Aircraft response to control inputs was predictable requiring minimal pilot workload. However, the vibration continued to increase above the levels experienced at 45° nacelle. The vibration was distracting and the largest contributor to pilot workload at 61° nacelle. Despite the vibration, airspeed was maintained within ± 2 knots, heading was captured within 2°, and altitude was maintained ±20 ft. Pilot workload was low for the task and an HQR of 2 was assigned.

75° nacelle, 80 knots. Control strategy for 75° nacelle was the same as 61° nacelle. The distracting vibration experienced at 61° was reduced for 75° nacelle. However, sideslip wandered throughout the standard rate turn, resulting in small altitude deviations. At the 75° nacelle configuration, deviations from desired parameters took longer to develop and were easier to correct than at higher airspeeds where the aircraft's response to gusts or pilot inputs was much more sensitive. Airspeed was maintained within 2 knots, altitude was maintained within 10 ft and heading was captured within 2°. The most difficult task was maintenance after heading capture due to the wandering sideslip. An HQR of 3 was assigned for the workload required in the directional axis.

Level Turning Acceleration.

Procedure:

1. From level flight, roll to the standard rate turn.
2. Maintain the standard rate turn throughout the maneuver.
3. Perform transition from 75° nacelle and 80 knots, to 0° nacelle and 200 knots, targeting a slow to moderate nacelle rate.
4. Capture 200 knots and stabilize.
5. Complete task within 90 seconds.

Pilot workload was low during the initial acceleration from 75° nacelle as the nacelles were moved at a rate slightly less than 1 °/sec. As the nacelles passed through 30° an increase in aft longitude cyclic of ½ to ¾ inches was required to maintain altitude. Final airspeed was captured 3 knots below the target airspeed; altitude was maintained within ± 20 ft. The maneuver was completed in 83 seconds. The highest contributor to pilot workload was the increased aft cyclic required as nacelles rotated down through 30°. Overall pilot workload was low and an HQR of 3 was assigned to the task.

Level Turning Deceleration.

Procedure:

1. From level flight, roll to the standard rate turn.
2. Maintain the standard rate turn throughout the maneuver.
3. From stabilized flight at 0° nacelle at 200 knots, initiate deceleration using aft TCL.
4. At approximately 165 knots, initiate conversion with a slow to moderate nacelle rate.
5. Capture 75° nacelle at 80 knots, and stabilize.
6. Complete task within 90 seconds.

Initial pilot workload was low as the nacelles were rotated up from 0° at a rate of 1 °/sec. As the aircraft slowed below 100 knots, yaw response became unpredictable. Maintaining bank angle and coordinated flight required both lateral cyclic stick and pedal inputs. Altitude was maintained within + 10 ft to – 50 ft. Final airspeed was captured within 2 knots, but required most of the pilot's attention and a ½ to ¾ inch longitudinal cyclic stick input at ½ Hz. The maneuver was completed in 75 seconds. Directional workload below 100 knots was the highest and an HQR 3 was assigned to the task.

Constant Speed Climbs

Procedure:

1. From level flight, initiate 1000 feet per minute (fpm) climb while maintaining airspeed.
2. Capture and maintain the desired rate within 5 seconds.
3. Capture an altitude change of 1000 ft.

0° Nacelle, 200 Knots. Climb rate was controlled with changes in pitch attitude in this configuration. Raising the pitch attitude to initiate and maintain a 1000 fpm climb rate did not result in a significant change in airspeed requiring only a small TCL input to maintain speed. Climb rate was responsive to small changes in pitch attitude required to maintain a constant rate of climb. During the level off at the target altitude, the aircraft accelerated slightly, requiring a small aft TCL input to maintain target airspeed. Rate of climb was maintained within ± 100 fpm, airspeed was maintained within – 4 knots, and heading was maintained within ± 2°. Final altitude was captured within ± 10 ft. The highest workload experienced during the maneuver was a small aft TCL input required during level off to maintain constant airspeed. An HQR of 2 was assigned to the task.

30° Nacelle, 150 Knots. In the 30° nacelle configuration, pitch attitude was used to initiate and maintain the climb. The initial pitch increase did not significantly decrease airspeed, requiring only small TCL inputs required to maintain airspeed in the climb. Adjustments in climb rate required larger pitch changes compared to the 0^{o} nacelle configuration. As pitch attitude was leveled to capture the final altitude, the aircraft accelerated, requiring a moderate TCL reduction to maintain target airspeed. Climb rate was maintained within ± 150 fpm, airspeed was maintained at or 4 knots below the target and heading was maintained within ± 2^{o}. Final altitude capture was 40 ft high. The highest workload portion of the maneuver was airspeed maintenance during final altitude capture. An HQR 3 was assigned to the task.

45^{o} Nacelle, 130 Knots. In conversion mode, a coordinated use of TCL and longitudinal cyclic stick was required to initiate the climb and maintain airspeed. Additionally, every adjustment in climb rate required a corresponding correction in airspeed due to the coupled response of TCL or longitudinal cyclic stick with climb rate and airspeed. Capturing final altitude also required moderate, coordinated TCL and longitudinal cyclic stick inputs.

The pilot used the longitudinal acceleration cue, shown on Figure A.7, symbol #29 to compensate for the coupled aircraft response. The longitudinal acceleration cue indicated a non-accelerated flight condition when the acceleration cue was abeam the aircraft symbol (symbol #6, Figure A.7). The pilot used the cue to determine the desired constant speed pitch attitude and matched that pitch attitude using longitudinal cyclic stick. The TCL was then used to maintain desired climb rate. Using the longitudinal acceleration cue as the desired pitch attitude cue made required pitch commands more predictable and reduced pilot workload in the conversion mode.

During the maneuver, climb rates were maintained with ± 200 fpm with a maximum excursion of 240 fpm just prior to final altitude capture. Airspeed was maintained within ± 3 knots and heading maintained with ±2^{o}. Final altitude was captured within 30 ft. The highest workload was the simultaneous, coordinated TCL and longitudinal cyclic stick inputs required to maintain climb rate and airspeed throughout the maneuver. As with level turns, the HQR was dependent on pilot experience, a less experienced pilot assigned an HQR 5 while a more experienced pilot assigned an HQR of 3.

61^{o} Nacelle, 110 Knots. Immediately after converting to 61^{o} nacelle, a considerable vibration distracted the pilot from normal flying tasks. In this configuration, aircraft response to TCL and longitudinal cyclic stick was an uncoupled response in climb and airspeed respectively. Aircraft response to TCL was sensitive in this configuration making capturing and maintaining desired climb rate less predictable. Airspeed was easily maintained by keeping a constant pitch attitude of on or slightly above the horizon. During the maneuver, climb rate was maintained within +300 to -200 fpm, airspeed was maintained on or 4 knots below target, and heading was maintained within ±2^{o}. Final altitude capture was accomplished 70 ft higher than the target altitude. The highest workload was attributed to the sensitive climb rate response to TCL input. An HQR of 3 was assigned to the task.

75° Nacelle, 80 Knots. Vibration levels in this configuration were evident, but not as distracting as in the 61° nacelle configuration. In VTOL mode, there was a slight coupling of nose up pitch with TCL input during the initiation of the climb. Outside of the initial coupled response, additional coupling of TCL with pitch was minimal during the remainder of the maneuver. Aircraft climb rate was not as sensitive to TCL input when compared with the 61° nacelle configuration making climb rate capture, climb rate maintenance, and altitude capture easy and predictable. Climb rate was maintained within ± 150 fpm, airspeed within ± 2 knots, and heading within ± 2°. Final altitude capture was within ± 10 ft of the target altitude. The task required minimal pilot compensation resulting in an HQR of 2.

Constant Speed Descents

Procedure:

1. From level flight, initiate a 1000 feet per minute (fpm) descent while maintaining airspeed.
2. Attempt to capture and maintain the desired rate within 5 seconds.
3. Capture an altitude change of 1000 ft.

0° Nacelle, 200 Knots. In airplane mode, the control strategy was similar to a conventional airplane with thrust or TCL primarily controlling speed and pitch attitude controlling rate of descent. Aircraft response to TCL and longitudinal cyclic inputs was sensitive for both airspeed and rate of climb changes.

During this maneuver, the pilot also noted that the digital vertical tape display of airspeed (Figure A.7, symbol #35) provided poor airspeed trend information. This poor trend information prevented the pilot from precisely stabilizing on airspeed. The 10 knot increment and slow, small movement of the vertical tape coupled with the changing digital number did not enable the pilot to integrate airspeed rate of change to precisely target airspeed. Instead, the pilot made continuous airspeed adjustments about the targeted airspeed, "chasing" the digital airspeed indication.

During the descent, airspeed was maintained within ± 3 knots, heading within ± 2°, and climb rate within ± 200 fpm with one excursion to +300 fpm from the targeted descent rate. Final altitude capture was within ± 10 ft. The most difficult task was maintaining airspeed attributed to the sensitive control response in airspeed and to the poor trend information provided by the digital airspeed display. An HQR of 3 was assigned to the task.

30° Nacelle, 150 Knots. The 30° nacelle configuration also resulted in an uncoupled, conventional airplane control strategy. During the initial descent increased pitch power coupling was evident in that, as TCL input was reduced, the nose pitched down 3°. During the remainder of the maneuver, there was minimal coupling for the small inputs required to maintain airspeed and descent rate. Rate of descent was maintained within ± 200 fpm, airspeed within ± 3 knots, and heading within ± 4°. Final altitude was captured within ± 10 ft of the target altitude. The highest workload portion of the maneuver was compensating for the initial nose pitch down with TCL reduction. An HQR of 3 was assigned to the task.

45° Nacelle, 130 Knots. In conversion mode, the workload required to precisely perform the constant speed descent was high, due mostly to the coupled response between TCL and longitudinal cyclic. When the pilot increased rate of descent with TCL, the aircraft simultaneously decreased airspeed, requiring a forward cyclic correction. When the pilot input forward cyclic to correct airspeed, descent rate increased further, requiring an increase in TCL.

Maintaining constant airspeed and rate of descent required coordinated and simultaneous longitudinal cyclic and TCL inputs to compensate for the coupled aircraft response. During the maneuver, airspeed was maintained within ± 5 knots, with one excursion + 6 knots from the target. Rate of descent was maintained within ± 200 fpm with one excursion to + 400 fpm from target. Heading was maintained with ± 4° and final altitude was captured +40 ft from the target. The highest workload was attributed to the simultaneous, coordinated cyclic and TCL inputs required to compensate for the coupled response. Handling qualities ratings at 45° nacelle were most depend on pilot experience with a pilot with under 20 hours in the V-22 assigning an HQR 5, while a pilot with 200 hours V-22 experience assigned an HQR 4.

61° Nacelle, 110 Knots. Vibration levels in this configuration were apparent and slightly increased pilot workload. In this conversion mode configuration, control strategy was similar to that of a conventional helicopter with TCL controlling altitude and longitudinal cyclic stick controlling small corrections in airspeed. Aircraft response to pilot inputs in all axes was uncoupled and straightforward. Airspeed was maintained within ± 2 knots, heading within ± 1°, and rate of descent within ± 200 fpm. Final altitude was captured within ± 10 ft of the target. Completing the task required minimal pilot compensation resulting in an HQR of 2.

75° Nacelle, 80 Knots. Vibration levels at 75° nacelle were evident, but not as distracting as the vibrations at 61° nacelle. As with the previous configuration, the control strategy was straightforward and similar to that of a conventional helicopter. At 75° nacelle, a small, lightly damped LDO was evident. The pilot compensated for the LDO primarily with lateral cyclic stick. Airspeed was maintained within ± 2 knots, heading within ± 2°, and rate of descent within ± 150 fpm. Altitude capture was accomplished within 10 ft of target altitude. Low workload was required to maintain the LDO within desired tolerances resulting in an HQR 2 being assigned to the task.

Climbing Acceleration

Procedure:

1. Initiate climb rate of 500 fpm.
2. Maintain 500 fpm throughout the maneuver.
3. Perform transition from 75^o nacelle and 80 knots, to 0^o nacelle and 200 knots, targeting a slow to moderate nacelle rate.
4. Capture 200 knots and stabilize.
5. Task ends while still in climb or descent.
6. Complete task within 90 seconds.

A climbing acceleration was chosen to evaluate the workload required to execute a maneuver such as an instrument departure or a missed approach while maintaining a constant climb rate. A nacelle rate of 1 ^{o}/sec was used for the maneuver. Initiating the maneuver by rotating nacelles forward and adding power increased the aft cyclic required maintaining climb rate. Aft cyclic requirements were greatest as the nacelles passed 30^o, requiring ¾ to one inch aft longitudinal cyclic stick to maintain climb rate.

Crew coordination was required for the pilot to maintain the targeted climb rate and heading while managing the pitch attitude and anticipating the capture of the desired airspeed. The pilot not at the controls relayed nacelle angle, airspeed, heading, and climb rate information to enable the pilot at the controls to complete the task. Heading was maintained within ± 2^o, climb rate within ± 150 fpm with one excursion of -300 fpm during the transition past 30^o nacelle, and airspeed was captured exactly. The maneuver was completed in 75 seconds. The highest workload was maintaining a targeted climb rate while rotating the nacelles forward. An HQR of 4 was assigned to the task. If a targeted climb rate was not required during the transition, the workload would have decreased considerably.

Descending Deceleration

Procedure:

1. Initiate descent rate of 500 fpm.
2. Maintain 500 fpm throughout the maneuver.
3. Perform transition from 0^o nacelle and 200 knots, to 75^o nacelle and 80 knots targeting a slow to moderate nacelle rate.
4. Capture 80 knots and stabilize.
5. Task ends while still in climb or descent.
6. Complete task within 90 seconds.

A descending deceleration was chosen to evaluate the workload required during the descent portion of an approach. Nacelles were converted aft at a rate of slightly greater than 1 ^{o}/sec. As the maneuver was initiated with a reduction of TCL and aft nacelle rotation, increasing forward cyclic was required to maintain descent rate. As the aircraft decelerated to 100 knots, aircraft response to TCL and longitudinal cyclic stick became coupled, requiring large, coordinated TCL and longitudinal cyclic inputs to maintain descent rate while managing the deceleration to capture the targeted airspeed. Heading was maintained within 3°. Rate of climb was maintained within ± 150 fpm until decelerating below 100 knots when rate of climb was maintained within ± 300 fpm. Airspeed was captured within ± 2 knots. The maneuver was completed in 73 seconds. The highest workload was the simultaneous maintenance of descent rate while capturing airspeed and moving nacelles aft. An HQR 5 was assigned to the task for the high workload required to maintain targeted descent rate during the deceleration through 100 knots. As with the climbing acceleration, if a specific descent rate was not targeted, workload would have decreased.

Unusual Attitude Recoveries

Unusual attitude recoveries were initiated by having the pilot evaluating the maneuver close his eyes while the other pilot maneuvered the aircraft into an unusual attitude. Once the aircraft was in the selected unusual attitude, the controls were transferred to the pilot evaluating the maneuver and the aircraft was recovered using the procedures listed in Table 3.1.

Unusual attitude recoveries were flown for many different unusual attitudes during flight test. The maneuvers included in this paragraph reflect only the most critical unusual attitude recoveries discovered during the evaluation.

Table 3.1: Unusual Attitude Recovery Procedures

Flight Mode	Unusual Attitude	Recovery Technique
Airplane	Nose High Straight and level to +20°	• Add power if airspeed low or decreasing • Smoothly lower nose to horizon • Smoothly roll wings level
	Nose Low Straight and level to –20°	• Smoothly roll wings level • Reduce power if speed increasing or high • Pull nose smoothly to horizon
	Excessive Bank >Std rate to Flight Clearance	• Reduce power • Smoothly roll wings level
Conversion mode and Helicopter	Nose High Straight and level to +20°	• Add power if airspeed low or decreasing • Smoothly lower nose to horizon • Use forward nacelle to help recover from nose high attitude • Smoothly roll wings level
	Nose Low Straight and level to –20°	• Smoothly roll wings level • Reduce power if speed increasing or high • Pull nose smoothly to horizon
	Excessive Bank >Std rate to Flight Clearance	• Reduce Power • Smoothly roll wings level

0^o Nacelle, 200 Knots. Unusual attitude recovery was made from a 20^o nose low, high power, accelerating condition. Aircraft response to longitudinal was crisp and predictable. Descent rate was easy to arrest by increasing the nose attitude above the horizon. The nose up attitude and reduction in TCL stopped the aircraft's acceleration and reduced airspeed. While normal acceleration was not significantly increased during the maneuver, the pilot was not concerned with over stressing the aircraft during a nose low recovery because of the structural load-limiting feature of the V-22. Recovering from a nose low, high power, accelerating unusual attitude within desired tolerances was easy. An HQR of 2 was assigned to the task.

30^o Nacelle, 150 Knots. Unusual attitude recovery was made from a 20^o nose high attitude. The nose high attitude induced a stall, which corresponded to a significantly increased rate of descent, but minimal airframe buffeting or pitch break. Aircraft recovery was initiated using nose down and an increase in TCL. Aircraft response to TCL was sluggish, remaining in the stalled condition for several seconds after initial TCL input. While the control strategy was straight forward, the sluggish aircraft response to TCL inputs to recover from the stall prevented the pilot from recovering in the desired altitude band of 200 ft. An HQR of 5 was assigned to the maneuver for the workload required to recover within the targeted altitude band.

45^o Nacelle, 130 Knots. The unusual attitude recovery was initiated from a 20^o nose low, 20^o angle of bank attitude. Aircraft response in both the longitudinal and lateral axis was smooth and predictable. Recovery from a nose low, excessive angle of bank condition required very little pilot workload. An HQR of 2 was assigned to the task.

61^o Nacelle, 110 Knots. The aircraft was placed in a 20^o nose low, high power condition. The combination of nose low and nacelle angle resulted in the relative nacelle angle and corresponding thrust vector to be 50^o down from vertical. This resulted in a rapidly accelerating condition. To correct for the acceleration, the pilot commanded a large, rapid reduction in TCL and simultaneous nose up attitude. While effective at reducing the acceleration, the corrected nose high attitude placed the thrust vector 15^o-20^o relative to the vertical axis in a low power condition. With the thrust vector close to vertical at a low power setting, descent rate increased until the pilot increased TCL. The recovery was complete 350 ft below the initial altitude. The highest workload was managing both descent rate and acceleration in the nose low, high power condition. An HQR of 4 was assigned to the task.

75^o Nacelle, 80 Knots. Unusual attitude recovery was initiated from a 10^o nose low, 10^o angle of bank condition. The pilot recovered using aft TCL and aft longitudinal cyclic stick. During recovery, aircraft accelerated approximately 10 knots. This airspeed increase was beyond the structural fatigue limits of the rotor head at 75^o nacelle angle. As a result of the increased airspeed, the conversion protection feature of the aircraft automatically rotated the nacelles forward, further accelerating the aircraft. The increased acceleration required the pilot to further decreased TCL, increase pitch attitude, and input aft nacelle angle. The highest workload during the maneuver was

compensating for the acceleration caused by conversion protection. An HQR 5 was assigned to the task.

Summary

The handling qualities for basic instrument maneuvers were deemed acceptable to proceed on to the next phase of testing, instrument navigation and approaches. While most of the maneuvers resulted in HQRs of 2 or 3, there were a significant number of maneuvers that resulted in HQRs or 4 or 5. Most of the higher HQRs corresponded to maneuvers in conversion mode at 45^o nacelle or for a maneuver that combined a transition or conversion with another maneuver such as a climb or descent. A table of maneuvers, nacelle configuration and HQRs assigned is presented in Table A.6.

Instrument Navigation and Approaches

Instrument navigation and instrument approaches were conducted in accordance with published IFR charts and approach plates while under air traffic control direction. The results for instrument procedures under VMC with the helmet mounted hood and under actual IMC were similar. The AFFTC descriptor rating scale was used to describe the handling qualities associated with each maneuver because of the numerous tasks required to perform instrument navigation and approaches.

Instrument Departure

Procedure:

1. Don instrument hood.
2. Perform hover takeoff, begin transition to 0^o nacelle, and continue climb on runway heading.
3. Achieve 75^o nacelle by 300 ft above ground level (AGL).
4. Target 1000 fpm rate of climb.
5. At 500 ft AGL, initiate 90 deg heading change and transition to 0^o nacelle, landing gear up, 180 knots.
6. Level off at 2000 ft AGL, 180 knots.

Three instrument departures were conducted during the evaluation. At the initiation of the instrument departure, the aircraft lifted smoothly into a hover and remained stable in the hover with minimal pilot compensation. The nacelles were rotated forward to 75^o by 300 ft using a moderate nacelle rate. An airspeed climb schedule was not targeted as targeting specific airspeed and nacelle combinations in a climb would require numerous pitch corrections creating excessive pilot workload. Instead, the nose was maintained on the horizon while the nacelles transitioned through the VTOL mode region and the pilot accepted the resulting acceleration and airspeed. Targeting 1000 fpm during the transition from hover to 45^o nacelle required small TCL inputs.

As the nacelles rotated forward past 45°, the pilot changed control strategy from TCL controlling climb to using longitudinal cyclic stick to control climb. During this transition, aircraft climb rate decreased significantly, requiring the pilot to raise the nose approximately 10° above the horizon to maintain the targeted climb rate. Once the new climb attitude was set, maintaining climb rate was easy. Capturing targeted airspeed within 5 knots was also easy utilizing aft TCL with the aircraft at 0° nacelle. Target altitude was captured within 50 ft.

During one instrument departure, a rapid nacelle rate was used to transition from a hover to airplane mode. This noticeably increased workload required and decreased the precision of the maneuver with targeted airspeed being overshot by 13 knots and targeted altitude being overshot by 70 ft. For all nacelle rates, the control strategy change and relatively large pitch change required maintaining climb rate as the nacelles rotated forward past 45° was the highest workload of the maneuver. The pilot assigned an AFFTC of satisfactory to the instrument departure task.

En route Navigation

Procedure:

1. Fly at least two legs of an airway as depicted on an En Route Low Altitude Chart.
2. Include at least one turning fix.

The VOR and TACAN were utilized to navigate along published Victor Airways. All en route navigation was conducted in airplane mode at 0° nacelle from 200 to 220 knots. In level flight, airspeed was maintained within ± 2 knots and altitude within ± 50 ft. During en route climbs and descents, airspeed was maintained within 5 knots and altitude was captured within 50 ft. The aircraft's response to lateral cyclic during radial tracking tasks was predictable with negligible directional coupling or LDO. Targeted radials were tracked within 1° to 2°. The predictable aircraft response and stability of the aircraft in level flight resulted in minimal pilot workload required to fly en route instrument navigation in the V-22. An AFFTC of satisfactory was assigned to the task.

Holding

Procedure:

1. Enter the holding pattern per published procedures, adjusting airspeed to 180 knots. Perform at least one entry using a parallel, teardrop, and direct entry procedure.
2. Fly at least one full holding pattern.
3. Exit the pattern as directed by Air Traffic Control (ATC) clearance.

All en route holding was conducted in airplane mode. In this configuration, aircraft response to lateral cyclic stick to enter holding and aft TCL to reduce airspeed to holding airspeed was smooth and predictable with negligible coupling in other axes.

During turns in holding, airspeed decreased as the turn was held for 180°. Maintaining airspeed within 5 knots in the turn required a vigilant scan of the airspeed indication and an approximate 15% increase in mast torque commanded from the TCL. A similar reduction in TCL was also required to prevent climbing and accelerating during roll out from the turn.

As previously discussed in the basic instrument section, the digital airspeed display increased the difficulty in perceiving trends in airspeed and subsequently increased pilot workload required to maintain airspeed. The vigilance required to scan and maintain airspeed resulted in a less vigilant scan of altitude and a loss of 50 ft during the turn. In addition, the acceleration cue used to provide airspeed trend information (Figure A.7, symbol 29) was not reliable in a turn. The logic, which provided cue dynamics, sensed all aircraft acceleration. Because a constant speed turn is still subject to centrifugal acceleration, the cue indicated acceleration in the turn even though airspeed remained constant. Overall, the task of holding was more difficult than instrument navigation, but the compensations required to maintain desired tolerances were moderate. An AFFTC of satisfactory was given to the holding task.

Instrument Approaches

Instrument approaches were conducted at four nacelle and airspeed configurations, 30° nacelle and 150 knots, 45° nacelle and 130 knots, 61° nacelle and 110 knots, and 75° nacelle and 80 knots. PAR, ILS, TACAN, and VOR approaches were flown at Patuxent River, NAS and surrounding airfields in accordance with published approach procedures or as directed by ATC. The visual cueing environment was obscured by a helmet mounted hood or actual IMC. The source of visual obscuration (helmet mounted hood or actual IMC) or the type of approach flown did not significantly affect handling qualities during this phase of testing. For this reason, the results for all approach types and visual cueing environments are presented according to nacelle and airspeed configuration, which was a more consistent and dominant influence on handling qualities.

30° Nacelle, 150 Knots. The approach was initiated by a conversion from 0° nacelle, 220 to 200 knots, and 5° to 7° nose up pitch attitude. Initial aircraft deceleration was slow as the nacelles rotated up the first 10° to 20° with nose attitude remaining at 7° nose up. As the nacelles rotated up to 30° and airspeed reduced through 160 knots, the rate of deceleration rapidly increased causing a 10 knot under shoot of the targeted airspeed. The final airspeed was captured using an increase in TCL and lowering of pitch attitude. Once captured, airspeed maintenance was easy using small TCL inputs and maintaining the pitch attitude on or 1° to 2° below the horizon. Control strategy was straightforward with TCL primarily controlling airspeed and longitudinal cyclic stick primarily controlling altitude.

Conducting the conversion from airplane mode to the approach configuration while turning, or changing altitude, or both, further increased pilot workload. Converting to 30^{o} nacelle while maneuvering to the assigned heading or altitude required the pilot to simultaneously scan altitude, heading, airspeed, and nacelle angle while utilizing coordinated cyclic stick and TCL inputs to compensate for changes in aircraft response due to the nacelle angle change.

Aircraft response to lateral cyclic stick was sluggish requiring large angles of bank to effect small heading changes during the final portion of the approach. During a PAR, 10^{o} of bank angle was required to change heading 3^{o} as directed by the final approach controller. Maintaining the desired glideslope during PAR or ILS approaches was difficult because at 150 knots, glideslope angle was very sensitive to changes in descent rate.

Unique to the 30^{o} nacelle configuration was the 150 knot airspeed that prevented the pilot from lowering the landing gear until the approach was complete and a landing was assured. This required the pilot to rapidly rotate the nacelles aft to at least 75^{o}, slow to below 100 knots, and perform landing checks simultaneously and immediately after descending below the clouds.

During an ILS in actual IMC, the aircraft broke out of the clouds at 350 ft AGL. As soon as the runway was in sight at 350 AGL, the pilot quickly moved the TCL completely aft, and rotated the nacelles up at a medium to high nacelle rate while instructing the copilot to lower the landing gear and perform landing checks. As the nacelles were rotated aft, aircraft descent rate decreased as the thrust vector rotated up with the rotation in nacelles and airspeed decreased. Previous approaches under the instrument hood resulted in climbs during the conversion with the TCL forward of the aft stop. Conversion protection prevented the nacelles from being rotated aft at a high rate as the aircraft decelerated through 100 knots requiring the pilot to raise pitch attitude to reduce airspeed to further rotate the nacelles aft. At nearly the same time as the conversion protection becoming active, descent rate began to increase with full aft TCL. The pilot quickly increased TCL and captured desired descent rate after one overshoot.

Landings in the 30^{o} nacelle configuration were 2000 to 2500 ft past the intended TDZ at 60 to 70 knots. That distance increased to 3500 ft when the approach was offset 200 ft laterally from runway centerline. While control strategy was straight forward during the initial portion of the approach, the final approach to landing was extremely rushed and workload intensive because the final landing configuration was delayed until the last moments of the approach. An AFFTC rating of marginal was assigned to approaches conducted at 30^{o} nacelle and 150 knots.

45^{o} Nacelle, 130 Knots. Aircraft response to TCL and longitudinal cyclic input was predictable during initial airspeed capture. Once in the desired configuration, control strategy changed from a conventional airplane mode control strategy to a coupled response of altitude and airspeed with TCL and longitudinal cyclic inputs. Simultaneous, coordinated TCL and longitudinal cyclic inputs were required for airspeed and altitude corrections. The control strategy required at 45^{o} nacelle increased the workload required to maintain glideslope when compared to nacelle configurations with more straightforward control strategies. Lateral response was predictable and uncoupled in the yaw axis.

During a TACAN arcing approach, the nacelle conversion was delayed until turning to the final approach course. Aircraft configuration on the arc was 0^o nacelle and 180 knots. Converting to 45^o nacelle during the turn to the final approach course required the pilot to rotate nacelles aft, lower pitch attitude to initiate a descent, perform the landing checklist, capture the final approach course, and change control strategy from airplane mode to a the coupled control strategy. Further increasing pilot workload was the aircraft's tendency to climb as nacelles were rotated aft. The climbing tendency combined with the high workload and airspeed prevented a timely descent, resulting in the aircraft being approximately 500 ft above altitude at the final approach fix. Aircraft response was predictable to large control inputs used to correct for the altitude deviation. Delaying the nacelle conversion and transition to final approach configuration significantly increased pilot workload compared to performing the same task in level flight.

Once on the desired approach path, configuring for the landing was not difficult using a medium nacelle rate. The tendency of the aircraft to climb was not as pronounced as at 30^o nacelle and easily compensated using aft TCL inputs. Conversion protection did not become active during decelerations to land.

Landing within the TDZ was easy for approaches aligned with runway heading. For approaches offset laterally 200 ft from centerline, the aircraft landed 1000 ft long of the TDZ at 45 knots. Even though the landing was long, the touchdown speed of 45 knots enabled the aircraft to easily stop within the length of the runway, marginalizing the requirement to land on the TDZ.

The highest workload associated with approaches at 45^o nacelle and 130 knots was the coupled control strategy required in this configuration. As discussed in the basic instrument section, the workload and handling qualities required for the 45^o nacelle configuration were largely dependant on pilot experience and training. Additionally, delaying the conversion to 45^o until the final approach course significantly increased pilot workload resulting in an AFFTC rating of marginal. When conversions were performed in level flight, an AFTTC rating of satisfactory was assigned to approaches at 45^o nacelle and 130 knots.

61^o Nacelle, 110 Knots. During the conversion from 0^o nacelle to 61^o nacelle, the pilot was required to reduce pitch attitude from 7^o nose up to level on the horizon as the nacelles converted through 45^o. Also required at the same time was a change in control strategy from airplane mode with TCL controlling airspeed and longitudinal cyclic stick controlling altitude to a VTOL mode control strategy with TCL controlling altitude and longitudinal cyclic stick controlling airspeed. The aircraft also climbed with an upward

rotation of the nacelles causing the aircraft to deviate 50 to 80 ft in altitude and a 10 knot overshoot of desired airspeed during conversions to 61^{o} nacelle in level flight.

As with previous approaches, when the pilot delayed converting from airplane mode and 180 knots to the final approach configuration, workload increased markedly. The increase in workload was more pronounced for the larger nacelle angle change to 61^{o} nacelle. The tendency to climb was more pronounced than during conversions to 30^{o} and 45^{o} nacelle, requiring larger changes in pitch attitude to maintain a constant rate of descent. Scanning and adjusting bank angle also was more critical during the conversion to 61^{o} as the reduction in airspeed required a larger corresponding reduction in bank angle to maintain a standard rate turn. Converting prior to intercepting the final approach course significantly reduced the pilot workload.

Immediately after converting to 61^{o} nacelle an increase in aircraft vibration was apparent. The vibration was primarily in the lateral axis and occasionally caused biomechanical coupling in the lateral axis. The vibration was always apparent to the pilot and distracted the pilot from flying tasks.

The control strategy at 61^{o} nacelle was straightforward with an uncoupled response of airspeed and altitude with longitudinal cyclic stick and TCL inputs. Airspeed was stable maintaining a constant pitch attitude on or slightly above the horizon. When the pilot attempted to precisely target airspeed using constant small longitudinal cyclic stick inputs, airspeed fluctuated about the targeted airspeed ±2 to 3 knots while "chasing" the targeted airspeed on the digital airspeed display as previously discussed in the basic instrument maneuvers section. Airspeed was much more stable when the pilot maintained the nose on the horizon and accepted the airspeed corresponding to the nacelle setting. Maintaining a constant attitude to stabilize airspeed significantly reduced pilot workload. During some approaches, the pilot rarely scanned airspeed allowing the inherent stability of the aircraft to maintain airspeed with little pilot input or attention. Using the constant attitude method usually resulted in a stabilized airspeed within 1 to 2 knots and within 2 to 3 knots of the targeted airspeed with a low pilot workload.

Aircraft climb and descent rate was responsive to TCL input making changes in altitude timely and predictable. Lateral response of the aircraft was more responsive and predictable compared to the 30^{o} and 45^{o} nacelle configurations enabling the pilot to precisely capture headings as directed by final approach controllers during PAR approaches.

During the transition to land, aircraft response to aft TCL and moderate nacelle rotation rate to 75^{o} was predictable with only a slight tendency to climb with an aft rotation of the nacelles. The pilot easily compensated for the climb with aft TCL. Landing within the TDZ was also easy for straight in and approaches offset laterally 200 ft from runway centerline. Only a 10 knot deceleration and 14^{o} aft nacelle rotation were required to transition within landing limits.

While handling qualities were favorable for the 61° nacelle configuration, compatibility with faster fixed wing traffic was a concern. During an ILS approach at Andrews Air Force Base in IMC, the aircraft was instructed by ATC to execute a missed approach due to faster fixed wing aircraft overtaking the V-22 at 110 knots. The faster nacelle and airspeed configurations evaluated would have been more compatible with fixed wing traffic in the instrument pattern.

The 61° nacelle and 110 knot configuration corresponded to the lowest workload of all the nacelle configurations tested with the lateral vibration being the largest contributor to pilot workload. An AFFTC rating of satisfactory was given to the 61° nacelle configuration.

75° Nacelle, 80 Knots. The conversion to 75° nacelle and 80 knots was similar to the conversion to 61° nacelle with approximately 7° of nose down pitch attitude change required to prevent a climb as the nacelles rotated past 45°. Airspeed was easier to capture than at 61° nacelle as the rate of deceleration decreased for the higher nacelle angles making airspeed capture more predictable. All conversions to 75° nacelle were conducted in level flight, prior to turning to the final approach course.

Control strategy was straightforward and consistent with conventional helicopter control strategies with TCL controlling altitude and longitudinal cyclic stick controlling airspeed. As with 61° nacelle, airspeed was stable with the pitch attitude set to the horizon and accepting the airspeed that corresponded to the nacelle angle. Workload increased considerably when the pilot attempted to precisely target an airspeed using continuous small changes in pitch.

In the 75° nacelle configuration, the aircraft exhibited a lightly damped LDO, which caused un-commanded 1° to 2° heading changes. Aircraft response to lateral cyclic was sluggish increasing the pilot workload required to dampen the LDO. The characteristic LDO was of particular annoyance to the pilot during PAR approaches, which require precise 2° to 3° heading changes as directed by the final approach controller.

Aircraft response to TCL was predictable making descent to MDA and glideslope maintenance easy. The slower airspeed also enabled a more precise approach as the pilot was able to perceive and correct deviations in glideslope and course before the deviations became very large. The airspeed also decreased the workload of PAR final approach controllers for the same reason. The increased precision also increased pilot workload as numerous, small inputs were required to maintain precise course, radial tracking, and glidelsope control at 75° nacelle.

Landing within the TDZ was easy for straight in and approaches offset laterally 200 ft from runway centerline. No change to the aircraft configuration was required to land within the aircraft's landing limits. The slower airspeed also increased the precision with which the pilot could select the touchdown point. The highest workload of the 75°

nacelle configuration was compensating for the lightly damped LDO. An AFFTC rating of satisfactory was assigned to the 75° nacelle, 80 knot configuration.

Simulated Single Engine Missed Approaches

The evaluation of simulated single engine missed approaches focused on the ability of the aircraft to execute a missed approach in the selected nacelle and airspeed configuration, with the handling qualities being secondary to the evaluation. For this reason, no handling qualities rating scales were used during the simulated single engine missed approach evaluation.

Procedure:

1. Conduct a simulated single engine by limiting mast torque to 60%.
2. Fly an ILS, TACAN, or VOR approach.
3. Execute simulated single engine missed approach.
4. Conduct in day VMC only.

30° Nacelle, 150 Knots. To initiate the missed approach, a slow, deliberate nacelle movement was used to transition to airplane mode at 0° nacelle. As nacelle angle rotated down, the pilot input gradual, coordinated aft cyclic to maintain level flight or a slight climb. The aircraft did not descend during the nacelle transition enabling the aircraft to transition to airplane mode and climb out in the simulated single engine condition.

45° Nacelle, 130 Knots. Descent rate was more sensitive to downward nacelle rotation than with the 30° nacelle configuration. The transition to 0° nacelle required additional time and distance as both the nacelle angle change was larger and the nacelle rate was slower to minimize loss of altitude during the missed approach. The aircraft descended 200 ft during the missed approach. A climb rate was not possible until the aircraft had transitioned to 0° nacelle. Compared to the 30° nacelle configuration, executing a missed approach in a single engine condition was higher workload at 45° nacelle because of the energy management required during the transition to airplane mode.

61° Nacelle, 110 Knots. Aircraft descent rate was very sensitive to forward nacelle rotation, requiring the pilot to stop many times during the transition to prevent excessive descent rates and allow the aircraft to accelerate before continuing the transition to 0° nacelle. Executing a simulated single engine missed approach required eight miles to complete. Before a climb rate could be established in airplane mode, the aircraft was 8 miles from the airfield and had descended 250 ft. The 75° nacelle configuration was not attempted because the trend of increasing altitude loss and time required to transition with increasing nacelle angle indicated a favorable result was not likely.

Summary

The instrument navigation and approaches phase of the V-22 IMC evaluation demonstrated that the V-22 could operate in the IFR environment with satisfactory handling qualities. Transition from takeoff to en route flight in IMC in airplane mode at 0^{o} nacelle resulted in very favorable handling qualities and an AFFTC rating of satisfactory.

Of all the nacelle configurations evaluated for instrument approaches, only the 30^{o} nacelle, 150 knot configuration was given an AFFTC rating of marginal. The marginal rating was attributed mostly for the requirement to rapidly convert the nacelles up, decelerate, and configure the aircraft for landing after the airfield was in sight, which may be as low as 200 ft AGL for precision approaches. The 45^{o}, 61^{o}, and 75^{o} nacelle configurations were determined to have satisfactory handling qualities. Of all the nacelle configurations tested during instrument approaches, the 61^{o} nacelle configuration was found to have the most favorable handling qualities in the IMC environment.

For all nacelle configurations evaluated, the timing and rate of nacelle conversion from 0^{o} to the final approach configuration was found to have a significant impact on pilot workload. Conversions in level flight required significantly less workload than conversions while descending or turning to final approach course. Using a moderate nacelle rate for the conversion to final approach configuration also significantly reduced pilot workload compared to a high rate of nacelle movement.

During simulated single engine missed approaches, only the 30^{o} and 150 knots configuration executed a missed approach without a loss of altitude. The 45^{o} and 61^{o} nacelle configurations exhibited a very sensitive altitude response with a downward movement of the nacelles. This sensitive response resulted in up to 250 ft of altitude lost and eight miles required to perform simulated single engine missed approach at 61^{o} nacelle. Simulated single engine missed approaches were not evaluated at 75^{o} nacelle because of the unfavorable trend of altitude loss with increasing nacelle angle.

CHAPTER IV
ANALYSIS

Basic Instrument Maneuvers

The consistently highest workload basic instrument maneuvers under normal conditions were those requiring a transition or a conversion while maintaining a given flight parameter constant and performing a capture task. HQRs for these tasks ranged from 3 to 5 as shown in Table A.6. This result is not surprising since nacelle angle changes caused transients in pitch attitude, shifted center of gravity (CG), and changed aircraft control laws and control response requiring a change of control strategy for the pilot. The workload during all changing nacelle tasks was primarily in managing the vertical axis as the thrust vector changes, pitch attitude changes, and shifts in CG all contributed to workload in the vertical axis. The forward cyclic stick required during accelerating transitions and aft cyclic stick required during decelerating conversions was counter to the control inputs required in conventional aircraft and further increased workload during a moving nacelle task. As a result, the tasks corresponding to the highest HQRs were primarily vertical maneuvering tasks, the climbing acceleration and descending deceleration.

Unusual attitude recoveries also resulted in a wide range of HQR values. The characteristic of each recovery was entirely dependent on nacelle configuration and the reasons for the high or low workload during recovery were unique to each nacelle setting. Undesirable stall characteristics at 30^{o} nacelle contributed to the HQR 5 for that configuration. This was caused by the displaced thrust vector approximately 30^{o} higher than the wing, compounding the problems caused by the nose high attitude. The result was a sluggish aircraft response to pilot inputs during stall recovery. At 75^{o} nacelle, conversion protection made uncommanded forward nacelle rotation, resulting in excessive acceleration. The HQR 5 during this nose low recovery was attributed to conversion protection and resulting airspeed increase. Conversion protection is necessary to protect the rotor system from excessive flapping caused by blow back. In this instance it had a detrimental effect on handling qualities. For the low HQR ratings, smooth and predictable aircraft response to pilot input for the 0^{o} and 45^{o} nacelle configurations resulted in HQRs of 2. Unusual attitude recoveries illustrated the unique characteristics of each nacelle configuration, which were evident throughout the IMC evaluation.

During normal basic instrument maneuvers at fixed nacelle, the characteristics of each nacelle configuration became more evident. HQRs of 2 to 3 were assigned for fixed nacelle tasks at 0^{o}, 30^{o}, 61^{o}, and 75^{o}. For each of these configurations, control strategy was straightforward requiring a conventional airplane control strategy at 0^{o} and 30^{o} nacelle or a conventional helicopter control strategy at 61^{o} and 75^{o} nacelle. The control strategy required at these nacelle angles is consistent with the control law design of the aircraft discussed in Chapter I. The airplane mode configurations were similar in workload with 30^{o} nacelle being slightly higher because of the larger attitude changes required to effect a change in altitude and heading.

The characteristics of 61^o and 75^o nacelle were significantly different. Aircraft response at 61^o was more stable and predictable than 75^o, but vibrations at 61^o nacelle were the highest of all nacelle configurations, distracting to the pilot, and occasionally resulting in biomechanical coupling. At 75^o nacelle, the vibrations were decreased, but a lightly damped LDO was evident, increasing workload during heading maintenance and constant turn rate tasks.

The LDO at 75^o nacelle was characterized by equal roll and sideslip amplitudes of 5^o for a ϕ to β ratio of one with a period of five seconds. This LDO was also experienced under other flight operations such as terrain following and short takeoff and landing. Despite dedicated tests to evaluate the LDO, the exact cause is not fully understood. Probable causes of the LDO include proprotor wash interaction with the vertical tail and wing. The low auto flap setting at high nacelle angles was also a contributor to the LDO as other tests have demonstrated the LDO is greatly reduced when flaps are manually set to zero. High power settings were destabilizing and contributed to the LDO as well. The side-by-side tandem proprotor configuration also contributed to the LDO as the advancing nacelle's proprotor experienced increased relative wind compared to the retreating nacelle's proprotor. The increased relative wind increased lift on the advancing nacelle's proprotor, causing a further increase in sideslip and angle of bank.

Control power available to counter the LDO was also diminished at 75^o nacelle and 80 knots. LSG and DCP gain were phased out to zero at airspeeds above 60 knots and differential swashplate tilt was significantly reduced at 75^o nacelle 80 knots. Control power in this configuration, particularly in the lateral axis, was dependant on the conventional airplane control surfaces. The low dynamic pressure over the flaperons and rudders at 80 knots reduced control power available to counter the LDO.

Despite the LDO at 75^o nacelle, the airspeed maintenance task for 61^o nacelle and 75^o nacelle had similar characteristics. Placing and maintaining the nose on the horizon resulted in very stable airspeed and low workload for both nacelle settings. While the stabilized airspeed may have been 2 to 3 knots faster or slower than the targeted airspeed, the airspeed at which the aircraft stabilized did not change more than 1 to 2 knots with a level pitch attitude. When the pilot attempted to precisely capture and maintain targeted airspeed using small changes in pitch attitude, workload increased and airspeed was no closer to the target and less stable, fluctuating $\pm$ 2 to 3 knots as the pilot chased the digital airspeed display.

Aircraft control response at 45^o nacelle was coupled in altitude and airspeed. As expected, an increase in thrust with the engines tilted at a 45^o angle resulted in a simultaneous climb and airspeed increase. Likewise, a change in pitch also resulted in a change in altitude and airspeed. In this mode, the control laws are transitioning from using swashplate tilt to flaperon, elevator, and rudder for aircraft control. It is therefore not unexpected then that aircraft response and control strategy would not be straightforward in the 45^o nacelle configuration. The 45^o nacelle configuration resulted in the highest workload required to compensate for the coupled aircraft response. However, the HQR assigned was a function of pilot experience with a more experienced pilot assigning HQRs of 3 and 4 for constant speed climbs and descents while a less experienced pilot assigned HQRs of 5 for the same task.

Instrument Departure

The instrument departure resulted in a lower workload than the basic instrument maneuver of accelerating climb, which was intended to represent the workload required during an instrument departure. The reason for this discrepancy was attributed to the increased climb rate of 1000 fpm targeted during the instrument departure compared to the 500 fpm rate of climb targeted during the accelerating climb. The pilot captured climb rate later in the transition to airplane mode when capturing a 1000 fpm climb rate than when capturing 500 fpm climb rate during basic instrument maneuvers. Capturing and maintaining 500 fpm climb while still transitioning from VTOL, through conversion, to airplane mode was much more difficult than capturing 1000 fpm climb after the nacelles had transitioned through 45^o.

The pilot also did not target an airspeed climb schedule, but focused on performing the transition. The slight benefit of climb performance for targeting an airspeed climb schedule did not outweigh the greatly increased workload required to target airspeed while transitioning nacelles and targeting climb rate.

Also during this maneuver, the relationship of workload to nacelle transition rate was established. A greater rate of nacelle movement from VTOL to airplane mode resulted in rapid climb and acceleration, which prevented the pilot from achieving desired capture tolerances for altitude and airspeed and significantly increased workload. A more deliberate nacelle transition resulted in lower workload and greater precision during airspeed and altitude capture.

En route Procedures

En route procedures were flown exclusively in airplane mode at 0^o nacelle as this configuration is the most efficient flight configuration and is expected to be used unless the aircraft is taking off or established on an approach. The handling qualities results from basic instrument maneuvers and the instrument procedures phases were consistent in that workload was low for all tasks in airplane mode at 0^o nacelle. The greatest workload was during holding at 180 knots. At this airspeed, the aircraft is in the minimum power required configuration for 0^o nacelle. At this airspeed, aircraft response to TCL and longitudinal cyclic inputs were sensitive in that small power changes or cyclic stick inputs resulted in relatively large changes in airspeed or altitude. Overall, this did not have a significant impact on handling qualities as HQRs for airplane mode were never above 3 and all other axes were stable and had very predictable control response.

Instrument Approaches

Each nacelle and airspeed configuration had advantages and disadvantages. For all instrument approaches the timing and rate of nacelle conversion or transition had a large influence on pilot workload. Delaying the conversion to the final approach configuration until the turn to the final approach significantly increased pilot workload and detracted from maintaining the proper altitude profile during the approach. This conclusion is consistent with the basic instrument maneuver of the descending deceleration, which was assigned an HQR of 5. Delaying the conversion until the final approach course forced the pilot into this high workload maneuver during a critical portion of the approach. Converting nacelles prior to the turn to the final approach course, when the aircraft was in level flight, resulted in much lower workload. This result is also consistent with the basic instrument maneuver of a level deceleration, which was assigned an HQR of 3.

With almost unlimited nacelle and airspeed combinations inherent in a tiltrotor, the appropriate nacelle and airspeed combination depends on the conditions under which the aircraft is operating. An analysis of the four nacelle configurations evaluated during this test is presented in the following paragraphs.

30° Nacelle

The 30° nacelle, 150 knot configuration was the only configuration evaluated given an AFFTC rating of marginal. While the control strategy was straight forward, similar to that of a conventional airplane, the approach speed was above the maximum gear extension speed. This prevented the pilot from configuring the aircraft for landing until the field was in sight. During the deceleration, the aircraft tended to climb as nacelles rotated up and the thrust vector became more vertical. The pilot was also required to change control strategy from an airplane strategy to a helicopter strategy very close to the runway. Finally, conversion protection prevented the pilot from rotating the nacelles up during the final deceleration to land, requiring a pitch attitude increase to allow the nacelles to continue to be rotated above 75° for landing. Performing this already high workload task while simultaneously performing landing checks made the 30° nacelle configuration undesirable for instrument approaches under normal operating conditions.

However, during simulated single engine approaches, the 30° nacelle configuration was the only configuration tested that enabled a missed approach with no loss of altitude during a transition to airplane mode. The capability to execute a missed approach and transition to airplane mode would provide the capability to quickly proceed to an alternate airfield during a single engine emergency.

45° Nacelle

The 45° nacelle configuration was given an AFFTC rating of satisfactory, but was the highest workload of the other satisfactory configurations. The higher workload was attributed to the coupled control response of the aircraft in altitude and airspeed to TCL and longitudinal cyclic stick inputs.

During the basic maneuvers phase of the flight test, the 45° nacelle configuration had the highest HQR ranging from 3 to 5 compared to other all other nacelle configurations, which ranged from 2 to 3 for normal maneuvers of turns, climbs, and descents. Results were similar for instrument approaches with the coupled control response increasing pilot workload and decreasing the precision with which the pilot could fly the approach.

Decelerating to land within the TDZ also increased workload. However, touchdown speeds as low as 45 knots would enable the aircraft to stop within the length of the runway even if the aircraft landed beyond the TDZ. Numerous instrument approaches were safely conducted to a landing using inexperienced as well as experienced pilots under simulated and actual IMC in the 45° nacelle configuration. For this reason, this approach configuration was given an AFFTC of satisfactory despite the coupled control response.

An advantage of the 45° nacelle setting was compatibility with fixed wing aircraft. For slower nacelle and airspeed configurations, ATC directed pilots to execute a missed approach because of faster, fixed wing aircraft overtaking the V-22. The 130 knot speed of the 45° nacelle enabled the V-22 to perform instrument approaches at airports that predominately service aircraft with faster approach speeds.

61° Nacelle

The 61° nacelle 110 knot configuration had the most favorable handling qualities of all the configurations tested. The control strategy was straightforward and similar to that of a conventional helicopter. Aircraft response to TCL and cyclic stick input was predictable and there was no noticeable LDO characteristic. When the pilot maintained a level pitch attitude, airspeed maintenance was stable within 2 to 3 knots of the targeted airspeed and required a very low workload. HQRs were consistently low during the basic instrument phase of testing and were consistent with the results later acquired during the instrument approach evaluation.

The three disadvantages of the 61° nacelle configuration were a noticeable vibration, slow approach speed, and excessive altitude and distance required to transition to airplane mode during simulated single engine missed approaches. The vibration was distracting to the pilot and sometimes resulted in biomechanical coupling. Vibration induced fatigue was not an issue because the vibration was only experienced for the time required to conduct the approach. Had the pilot been subjected to this vibration for an extended period, fatigue would also have been a factor. The vibration also would decrease the comfort of the ride for any passengers embarked in the aft cabin. Passenger comfort is less of a concern for a military aircraft, but may be more of an issue if a civilian tiltrotor experiences similar vibrations.

As discussed in Results, Chapter III, the 110 knot speed resulted in ATC directing a missed approach during actual IMC because faster approaching aircraft were overtaking the V-22. The incompatibility of this nacelle airspeed configuration with faster fixed wing aircraft would increase the time required to recover during IMC and increase workload on both the pilot and ATC.

The aircraft also did not have a feasible missed approach capability under simulated single engine conditions. Over 200 ft of altitude and eight miles were required before the aircraft successfully transitioned to airplane mode and was able to climb out. While the 61^{o} nacelle configuration had the best handling qualities, it was not the best configuration for all conditions.

75^{o} Nacelle

The 75^{o} nacelle, 80 knot configuration also had a straightforward control strategy similar to conventional helicopters. Basic instrument maneuvers resulted in low HQRs of 2 to 3. Because of the slow airspeed, the pilot was able to maintain precise control of course and glideslope during ILS approaches, enabling the pilot and final approach controller to maintain tighter tolerances during PAR approaches. Maintaining a level pitch attitude to maintain airspeed resulted in stable airspeed with a low workload, as previously discussed in the basic instrument and 61^{o} nacelle analysis sections.

However, in the 75^{o} nacelle configuration, there was a noticeable LDO, which caused heading to wander unpredictably ± 2^{o} to 3^{o}. Damping this oscillation increased pilot workload and decreased the precision with which the pilot could capture and maintain heading. This LDO was also apparent during the basic instrument phase of the test. The slow 80 knot airspeed was also incompatible with faster fixed wing aircraft in the instrument pattern. Despite the LDO, precise tolerances could be held during instrument approaches because of the slow speed. Maintaining those precise tolerances increased pilot workload, as the pilot was required to make more frequent corrections during the approach.

CHAPTER V
RECOMMENDATIONS

During the execution of the IMC test plan, the V-22 successfully demonstrated the ability to navigate and conduct approaches under actual IMC. Having demonstrated this ability in simulated as actual IMC, the author concluded that the V-22 handling qualities were satisfactory and recommended for IMC operations.

Transition Point for Final Approach Configuration

The transition point for the conversion to final approach configurations had a significant impact on workload and handling qualities experienced by the pilot during an instrument approach. Transitioning during or after the turn to the final approach course resulted in very high workload and decreased the task tolerance held by the pilot. Converting nacelles in level flight, prior to the turn to the final approach course, resulted in favorable handling qualities and a manageable pilot workload. During instrument approaches the V-22 pilot should convert nacelles prior to turning on the final approach course.

Final Approach Nacelle Angle Configuration

One of the primary advantages of the tiltrotor design is the flexibility to change nacelle angle and corresponding aircraft flight regime to meet the current flight conditions. Limiting IMC operations to just one nacelle angle configuration would eliminate this advantage. It would follow that different nacelle configurations would be recommended for different conditions. The author's recommendations for nacelle configuration are discussed below.

The 61^{o} nacelle configuration had the most favorable handling qualities and should be the standard approach configuration. However, this configuration experienced distracting vibrations and at 110 knots was too slow to be compatible with faster fixed wing aircraft in the instrument pattern and did not have a single engine missed approach capability.

When compatibility with faster aircraft is a primary concern, the 45^{o} nacelle, 130 knot configuration is recommended. However, the coupled response of this configuration increased pilot workload and should be reserved for experienced tiltrotor pilots.

The most precise approaches were flown at the 75^{o} nacelle, 80 knot configuration. The slow speed enabled précised glideslope corrections, but the lightly damped LDO increased pilot workload during the heading maintenance task. The 75^{o} nacelle configuration is recommended when using COPTER approaches, which are written specifically for helicopters utilizing lower approach minimums.

The only configuration with an AFFTC rating of marginal was the 30° nacelle 150 knot configuration. This configuration should not be using for instrument approaches during normal operations. However, this configuration was also the only configuration tested that enabled a transition to airplane mode during a simulated single engine missed approach with no loss of altitude. The pilot should consider using the 30° nacelle configuration during single engine operations in IMC to maintain the capability to execute a missed approach.

Airspeed Control Strategy in VTOL and Conversion Mode

During the basic instrument phase and instrument approach phase of testing, stable airspeed was accomplished in VTOL and conversion mode by simply setting the desired nacelle angle and maintaining the aircraft nose on the horizon. The final airspeed captured was within ± 2 to 3 knots of the targeted airspeed. When the pilot attempted to exactly capture the targeted airspeed using small pitch corrections, the airspeed was not as stable, fluctuating ± 2 to 3 knots and workload increased significantly. While nacelle angle was fixed for evaluation purposes, an operational pilot could make 1° to 2° nacelle corrections while maintaining the nose on the horizon to increase precision of the final captured airspeed. It is recommended for IMC operations in VTOL and conversion mode, the pilot keep the nose attitude trimmed on the horizon and control airspeed using nacelle angle only.

CHAPTER VI
FUTURE CAPABILITES

With the V-22 entering full rate production less than a year ago, and a block upgrade acquisition strategy being used, improvements to the current design will be implemented. The sections below discuss future capabilities that should be implemented or considered to improve the IMC handling qualities capabilities of the V-22 or future tiltrotor or other VTOL designs.

Control Laws

One of the first challenges a tiltrotor pilot faces is the requirement to change control strategy as the aircraft transitions from VTOL mode, to conversion mode, to airplane mode. With fly by wire control systems, the possibility exists to write control laws that would enable the pilot to maintain the same control strategy throughout all modes of tiltrotor flight. The Marine (Vertical and Short Takeoff and Land) version of the Joint Strike Fighter may be considering just such a control arrangement.

While the advantage of consistent control strategy is reduced pilot workload, the complexity of such a system may cause unforeseen control problems or reduce the bandwidth and phase margin of aircraft response. A consistent control strategy, while useful in the IMC environment, may not result in the optimal control strategy for other environments in which the V-22 must operate, such as the shipboard environment. While the V-22 control law design is too mature to reasonably accommodate such a change in CLAWS, using a consistent control strategy throughout all flight regimes should be considered for future tiltrotor or other VTOL designs.

Airspeed Indication

As discovered during the basic instrument and instrument approach phases of testing, the pilot tended to "chase" the digital airspeed indication shown on the V-22 digital display. The vertical tape displayed behind the digital airspeed indication did not provide adequate airspeed rate of change cueing to the pilot. To compensate for this, the V-22 incorporates a longitudinal acceleration cue displayed on the attitude indicator (Figure A.7, symbol 29). Unfortunately, this cue indicated a longitudinal acceleration during turning flight because of the centrifugal acceleration experienced in a turn. This caused the longitudinal acceleration cue to provide a false indication to the pilot and contributed to the workload required to maintain constant speed in a turn. Future avionics software should be written to filter out the centrifugal acceleration component from the cue to provide an accurate longitudinal acceleration indication to the pilot during turning flight in addition to wings level flight.

Auto Nacelle

One of the highest drivers of handling qualities workload was transitions and conversions of nacelle angle. Much of this workload should be alleviated by automatically programming the nacelles to an ideal angle corresponding to airspeed. As the aircraft changed airspeed, the nacelles would program forward or aft relieving the pilot from the task of managing nacelle rate. Auto nacelle would also add complexity to the CLAWS and care would need to be taken during the design to prevent nacelle reversals if auto nacelle was engaged at a nacelle and airspeed configuration that was not along the automatically programmed path. This improvement is currently under development for the V-22 and has begun flight test.

Coupled Modes

Coupled modes, or autopilot as it is known in other aircraft, would relieve the pilot from the physical hand eye coordination workload required for flight and place the pilot in a systems manager role. A coupled modes capability integrated with auto nacelle would enable hands off flight from shortly after departure, through the en route phase, to an ILS approach, and finally to a hover. The technical implementation of coupled modes in a tilt rotor with the addition of moving the nacelles pose a considerable challenge. Not to be overlooked in any future coupled modes design is the crew interface, particularly the crew indication of the current state of the coupled mode system.

Any coupled mode system should provide the pilot a positive indication of which axes are coupled and which guidance is being followed. Additionally, the pilot should be alerted to changes in the coupled modes of the aircraft, from systems failures, to changing from heading to ILS guidance, automatic glideslope captures, and automatic deceleration profiles. Considerable pilot training is also required for coupled modes to be effective. The pilot must understand the system, how to operate it, and the crew coordination required so that both pilot and copilot are aware of the current state of the aircraft. A hands off, coupled modes system which includes easily operated and interpreted crew interface should be implemented in the V-22 and future tiltrotor designs. Coupled modes development and testing is scheduled to begin later in 2006.

REFERENCES

REFERENCES

1. Calise, A.J. and Rysdyk R.T. *Adaptive Model Inversion Flight Control for Tiltrotor Aircraft.* AHS 54th Annual Forum, Washington, DC, May 20-22, 1998.

2. Strand, T., *IMC Evaluation of the MV-22B Osprey.* Society of Experimental Test Pilots European Symposium, Rome Italy, November 2004.

3. Darcy, J., *V-22 Osprey Program Overview.* PMA-275 Public Affairs Officer brief for Okinawa, Japan Journalists, Feb 2006.

4. Goldstein, K.W., and Dooley L.W., *V-22 Control Law Development*. AHS 42nd Annual Forum, Washington, D.C., June 1986.

5. Mullaney, R.C., et. al., *Joint Evaluation of the V-22 Flight Director and Coupled Modes System.,* No. V22-TP-004/05, NAVAIR Test Plan, October 2005.

6. Strand, T., Leonard, W., Thorn, D., *V-22Instrument Flight Rules/Instrument Meteorological Conditions Evaluation*. No. V22-TP-012/02, NAVAIR Test Plan, 19 February 2004.

7. Cooper, G.E. and Harper R.P. *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities.* NASA Technical Note D-5153. Moffett Field, California: Ames Research Center and Cornell Aeronautical Laboratory, 1969.

8. Calise, A.J. and Rysdyk, R.T. *Research in Nonlinear Flight Control for Tiltrotor Aircraft Operating in the Terminal Area.* NASA-CR-203112, 1 September 1995 – 31 August 1996.

9. Strand, T., *V-22 Instrument Flight Rules/Instrument Meteorological Consitions Evaluation.* NAWCADPAX/TR-2004/121, NAVAIR MV-22 IMC Report of Test Results, 2 August 2004.

10. Civil Tiltrotor Group, *Noise Abatement Approach Test Flight Terminal Area Operations Test Flight.* 3 June 1998.

11. Bell Boeing the Tiltrotor Team. *Tilt Rotor Handling Qualities Short Course Notes.*

12. A1-V22AB-NFM-000, *Preliminary NATOPS Flight Manual navy Model MV-22B Tiltrotor.* 15 May 2005.

APPENDIX

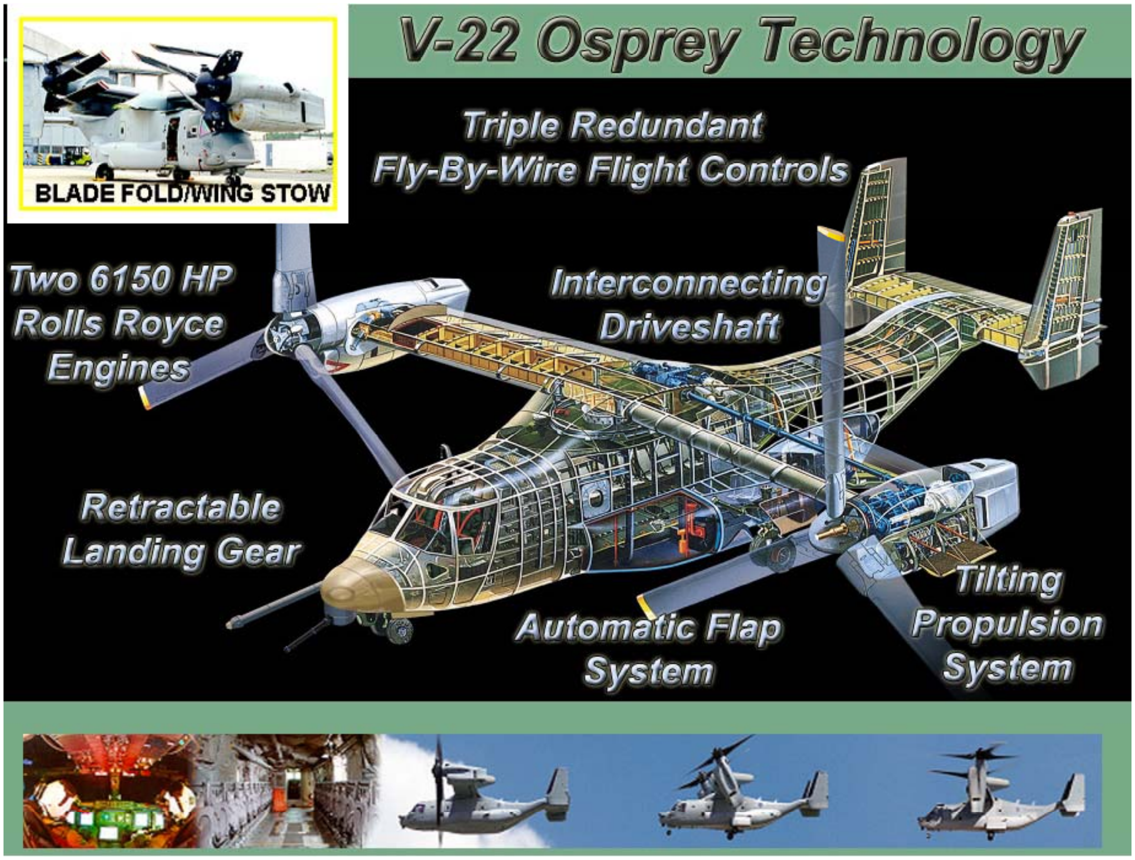

Figure A.1
V-22 Schematic

Figure A.2
V-22 Cockpit Flight Controls and Displays

Figure A.3
Thrust Control Lever

Figure A.4
Primary Flight Display

Figure A.5
Horizontal Situation Display

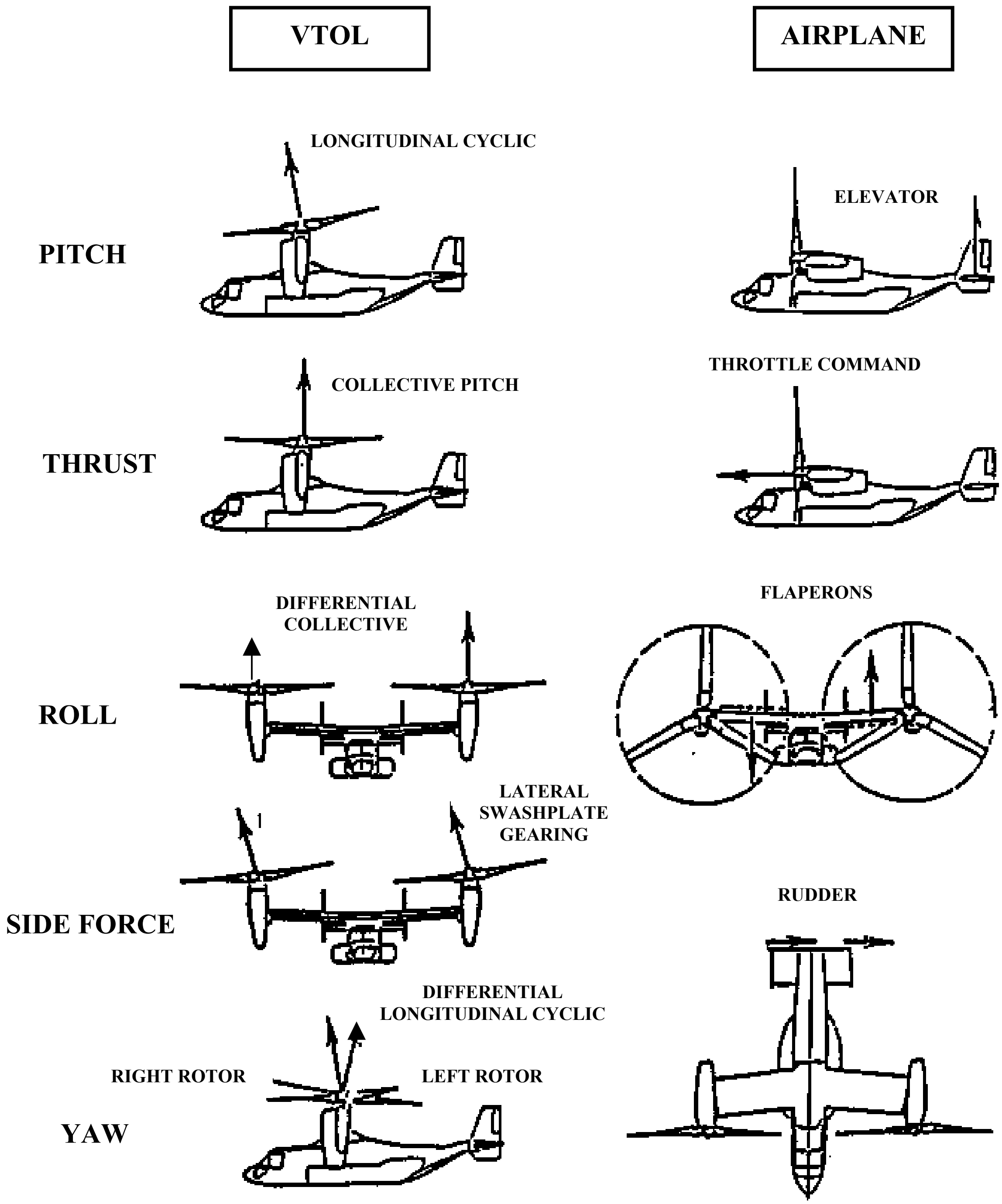

Figure A.6
V-22 Control Mechanisms

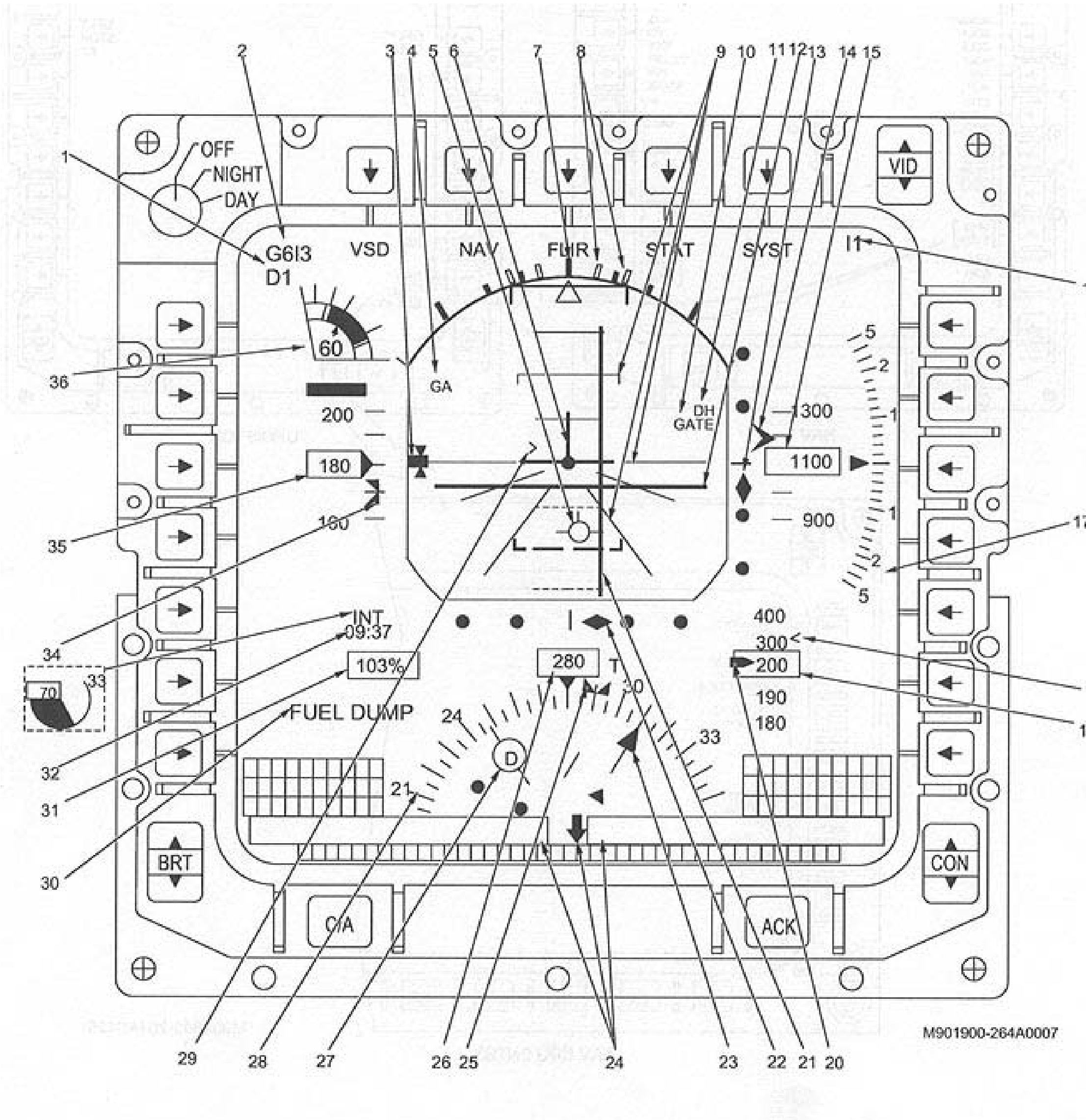

Figure A.7
Primary Flight Display
(With Callouts, see Figure A.8)

1	Declutter Level Indicator
2	Navigation System Status
3	Power Command Cue
4	Go Around (GA)
5	Flight Path Vector (FPV)
6	Aircraft Symbol
7	Bank Angle
8	Turn Rate Indicator
9	Pitch Scale
10	GATE Indicator
11	DH Indicator
12	Flight Director Pitch Command Bar
13	Glide Slope Deviation Indicator
14	Flight Director (FD) ALT Indicator
15	Barometric Altitude
16	Attitude Source
17	Vertical Velocity Indicator
18	Radar Altitude Low Set Pointer
19	Radar Altitude
20	FD HVR Indicator
21	Flight Director Lateral Command Bar
22	Lateral Deviation
23	Course Deviation Indicator (CDI)
24	Caution Advisory Boxes and Indicator
25	Flight Director Heading Indicator
26	Current Aircraft Heading
27	Bearing Needle
28	Compass Card
29	Longitudinal Acceleration Caret
30	FUEL DUMP Indicator
31	Average Mast Torque
32	INT
33	Stall Attack Indicator
34	FD Speed Indicator
35	Indicated Airspeed (IAS)
36	Nacelle Angle

Figure A.8
Primary Flight Display Symbols

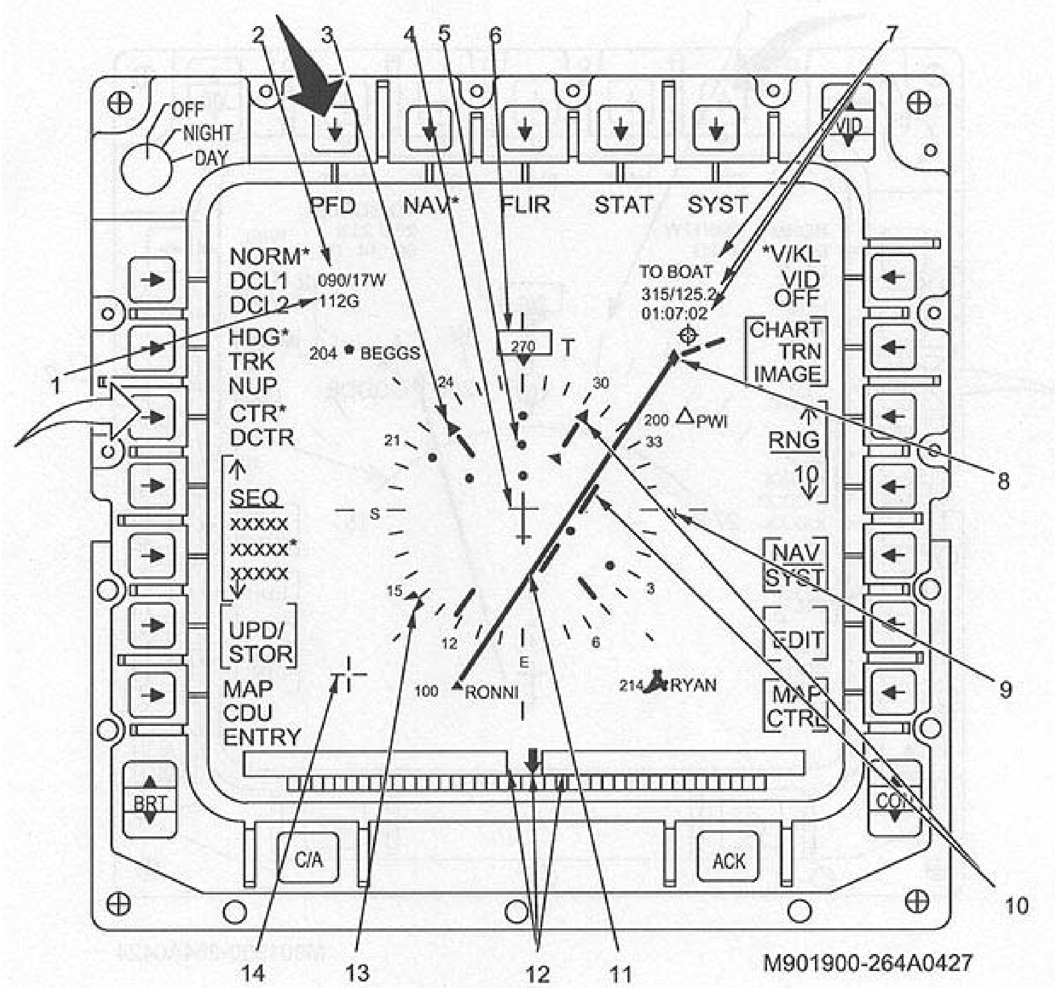

Figure A.9
Horizontal Situation Display
(With Callouts see Figure A.10)

Display Symbology

1 Ground Speed
2 Wind
3 Bearing Needle
4 Aircraft Symbol
5 Trend Dots
6 Current Aircraft Heading
7 Active Waypoint Information
8 Waypoint Symbols
9 Compass Card
10 Course Deviation Indicator (CDI) with To/From Indicator
11 Flight Plan Legs
12 Caution/Advisory Boxes and Indicator
13 Flight Director Heading Indicator
14 Target Cursor

Figure A.10
Horizontal Situation Display Symbols

Table A.1: VMC Under Hood Basic Instrument Flight Maneuvers

Flight Task	A/S (kcas)	Alt (ft AGL)	NAC (deg)	RPM (%)	Gear	Comments
Level Accel	80-200	>1000	75-0	100	Up	AFCS ON
Level Decel	200-80		0-75		Up	
Level Turns	200	>1000	0	84	Up	180 deg L or R standard rate turns, AFCS ON
	150		30	100	Up	
	130		45		Down	
	110		61		Down	
	80		75		Down	
Level Turning Accel	80-200	>1000	75-0	100	Up	AFCS ON, Maintain Standard Rate
Level Turning Decel	200-80		0-75		Up	
Climbs	200	>1000	0	84	Up	Climbs at 1000 fpm, AFCS ON
	150		30	100	Up	
	130		45		Down	
	110		61		Down	
	80		75		Down	
Climbing Accel	80-200	>1000	75-0	100	Up	Climbs at 500 fpm, AFCS ON
Climbing Decel	200-80		0-75		Up	
Descents	200	>1000	0	84	Up	Descents at 1000 fpm, AFCS ON
	150		30	100	Up	
	130		45		Down	
	110		61		Down	
	80		75		Down	
Descending Accel	80-200	>1000	75-0	100	Up	Descents at 500 fpm, AFCS ON
Descending Decel	200-80		0-75		Up	
IMC Unusual Attitudes	200	>1000	0	84	Up	AFCS ON
	150		30	100	Up	Nose High=Straight and level to +20°
	130		45		Down	Nose Low =Straight and level to -20°
	110		61		Down	Nose Low =Straight and level to -20°
	80		75		Down	Excessive Bank= > Std rate to flight clearance

Table A.2: En Route and Instrument Approach Maneuvers

Flight Task	A/S (kcas)	Alt (ft PA)	NAC (deg)	RPM (%)	Gear	Comments
PAR Approach	150	ATC assigned	30	100	Up	Execute precision approach IAW NATOPS and FLIP.
	130		45		Down	
	110		61		Down	
	80		75		Down	
ILS Approach	150	ATC assigned	30	100	Up	Execute precision approach IAW NATOPS and FLIP.
	130		45		Down	
	110		61		Down	
	80		75		Down	
VOR Approach	150	ATC assigned	30	100	Up	Execute non-precision approach IAW NATOPS and FLIP.
	130		45		Down	
	110		61		Down	
	80		75		Down	
TACAN Approach	150	ATC assigned	30	100	Up	Execute non-precision approach IAW NATOPS and FLIP.
	130		45		Down	
	110		61		Down	
	80		75		Down	
En Route NAV	A/R	ATC	0	84	Up	Execute NAV route IAW NATOPS and FLIP.
En Route Holding	A/R	ATC	0	84	Up	Execute holding pattern IAW NATOPS and FLIP.
Missed Approach	150-A/R	DH or MDA	30-A/R	100	Up	Execute procedure IAW NATOPS and FLIP.
	130-A/R		45-A/R		Down	
	110-A/R		61-A/R		Down	
	80-A/R		75-A/R		Down	
Sim Single Engine Approach	150	ATC assigned	30	100	Up	Execute approaches to landing and go-around at DH or MDA. VMC under hood only.
	130		45		Down	
	110		61		Down	
	80		75		Down	
Offset Approach	150	ATC assigned	30	100	Up	VMC under hood only.
	130		45		Down	
	110		61		Down	
	80		75		Down	
Instrument Takeoff	0-80	G.L.-2000	A/R	100	Down	As described in paragraph 5.1.2.1

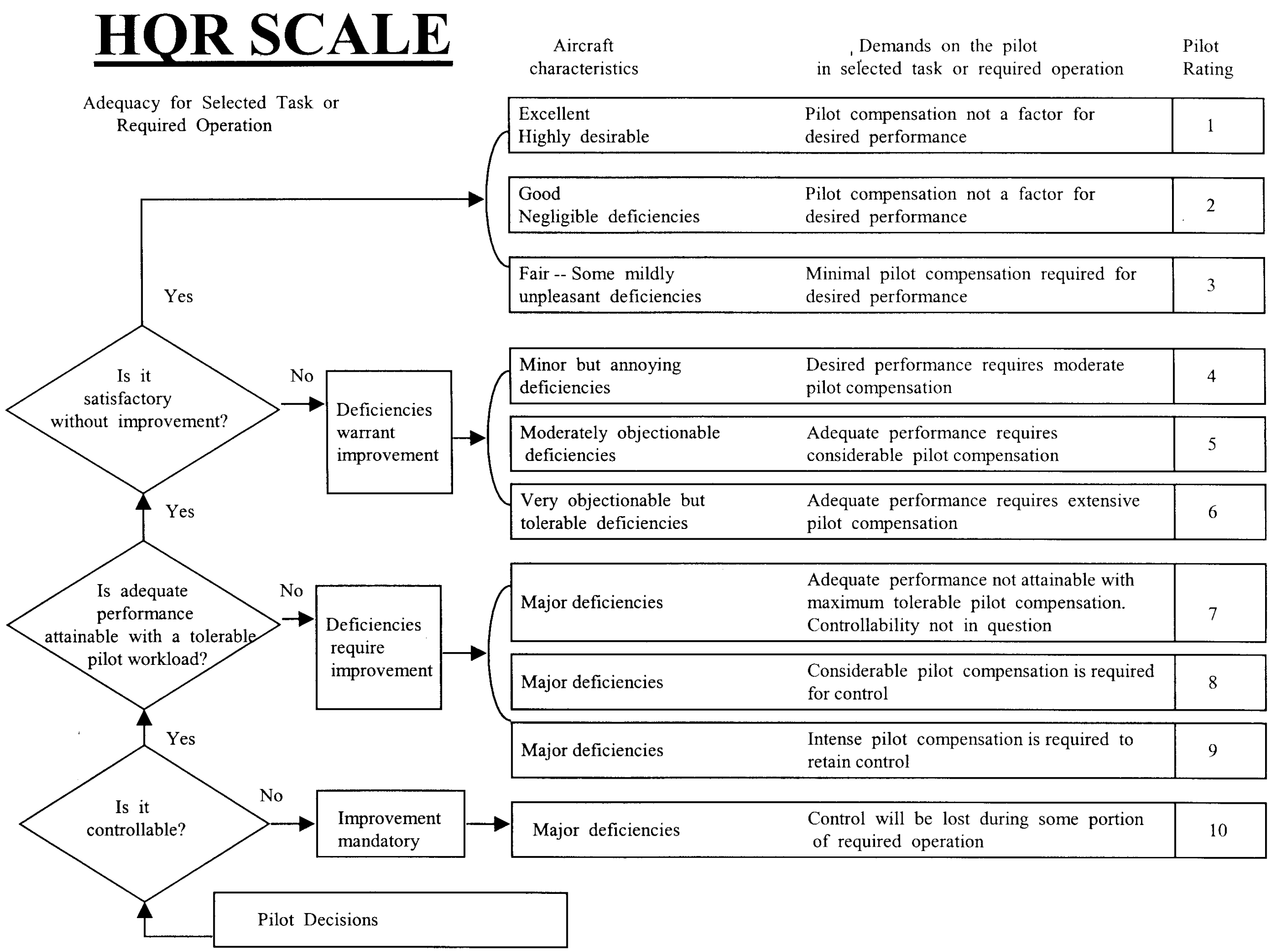

Figure A.11
Handling Qualities Rating Scale

Table A.3: Performance Criteria for Basic Instrument Flight

Task Element	Heading		Airspeed		Altitude		Vertical Speed Rate		Turn Rate	
	Desired	Adequate	Desired	Adequate	Desired	Adequate	Desired	Adequate	Desired	Adequate
Level Accel	±5°	±10°	±5 kts	±10 kts	±75 ft	±150 ft	N/A	N/A	N/A	N/A
Level Decel	±5°	±10°	±5 kts	±10 kts	±75 ft	±150 ft	N/A	N/A	N/A	N/A
Level Turn	Capture Hdg ±5°	Capture Hdg ±10°	±5 kts	±10 kts	±75 ft	±150 ft	N/A	N/A	±1/4 Std Rate	±1/2 Std Rate
Level Turning Accel	N/A	N/A	Capture ±5 kts	Capture ±10 kts	±75 ft	±150 ft	N/A	N/A	±1/4 Std Rate	±1/2 Std Rate
Level Turning Decel	N/A	N/A	Capture ±5 kts	Capture ±10 kts	±75 ft	±150 ft	N/A	N/A	±1/4 Std Rate	±1/2 Std Rate
Climbs	±5°	±10°	±5 kts	±10 kts	Capture ±75 ft	Capture ±150 ft	±200 fpm	±400 fpm	N/A	N/A
Climbing Accel	±5°	±10°	Capture ±5 kts	Capture ±10 kts	N/A	N/A	±300 fpm	±500 fpm	N/A	N/A
Climbing Decel	±5°	±10°	Capture ±5 kts	Capture ±10 kts	N/A	N/A	±300 fpm	±500 fpm	N/A	N/A
Descents	±5°	±10°	±5 kts	±10 kts	Capture ±75 ft	Capture ±150 ft	±200 fpm	±400 fpm	N/A	N/A
Descending Accel	±5°	±10°	Capture ±5 kts	Capture ±10 kts	N/A	N/A	±300 fpm	±500 fpm	N/A	N/A
Descending Decel	±5°	±10°	Capture ±5 kts	Capture ±10 kts	N/A	N/A	±300 fpm	±500 fpm	N/A	N/A
Recovery from Unusual Attitude	Maint. ±5°	Maint. ±10°	Maint. ±5 kts	Maint. ±10 kts	±200 ft	±300 ft	N/A	N/A	N/A	N/A

Table A.4: Air Force Flight Test Center (AFFTC) Descriptor Evaluation Scale

How Well Does the System Meet Mission/Task Requirements	Descriptors	Rating	Nature of Recommended Changes
Some or all requirements very well met.	Excellent, Outstanding, Superior, First Rate	Satisfactory	None Required
Some or all requirements well met; good enough as is.	Good	Satisfactory	Enhancements
Meets requirements; can do the job, but not as well as it could or should	Fair, Pretty Good, Tolerable	Satisfactory	Desire Improvements to Capability or Usability
Minimum level of acceptable capability and/or some noncritical requirements not met.	Borderline, Just or Barely	Marginal	Highly Desirable/Strongly Recommended to Reduce Risk in Operational Test or Field Use
Does not meet some critical requirements	Poor, Deficient, Unsuitable, Bad	Unsatisfactory	Substantial Changes Required to Achieve Satisfactory Capability
Does not meet most critical requirements.	Very or Extremely Bad, Poor, Deficient, Unsuitable	Unsatisfactory	Major Changes Required to Achieve Satisfactory Capability
Mission not possible.	Unusable, Unsafe or Dangerous	Unsatisfactory	Changes Mandatory to Meet Mission or Make Safe

Table A.5: Performance Criteria for Instrument Navigation and Approaches

Task Element	Heading		Airspeed		Altitude		Course Deviation		Glideslope Deviation	
	Desired	Adequate	Desired	Adequate	Desired	Adequate	Desired	Adequate	Desired	Adequate
ITO	±5°	±10°	±5 kts	±10 kts	Capture Alt±75 ft	Capture Alt±150ft	N/A	N/A	N/A	N/A
PAR Approach	±5°	±10°	±5 kts	±10 kts	DH ±25ft	DH ±50ft	Final HDG±3°	Final HDG±5°	Slightly above/ below	Well above/ below
LOC Intercept	N/A	N/A	Tgt ±5 kts	Tgt ±10 kts	±75ft	±150ft	No overshoot of final crs; no tendency to S-turn	<1/2 dot overshoot of final crs; slight S-turn	N/A	N/A
ILS Approach	±5°	±10°	±5 kts	±10 kts	TDZ 200 ft long x 20 ft wide	TDZ 500 ft long x 40 ft wide	1/2 dot	1 dot	1/2 dot	1 dot
LOC & BC LOC Approach	±5°	±10°	±5 kts	±10 kts	MDA ±50 ft	MDA ±100 ft	1 dot	2 dots	N/A	N/A
VOR & TACAN Approach	±5°	±10°	±5 kts	±10 kts	MDA ±50 ft	MDA ±100 ft	1/2 dot	1 dot	N/A	N/A
Missed Approach	N/A	N/A	±5 kts	±10 kts	DH –50 ft	DH -75 ft	N/A	N/A	N/A	N/A
Offset Approach	N/A	N/A	±5 kts	±10 kts	N/A; TDZ 200ft long x 20ft wide	N/A; TDZ 500ft long x 40ft wide	N/A	N/A	N/A; TD w/no hard ldg & no bounce	N/A; TD w/no hard ldg & no bounce
Enroute NAV	±5°	±10°	±5 kts	±10 kts	±50 ft	±100 ft	1 dot	2 dots	N/A	N/A
Holding	±5°	±10°	±5 kts	±10 kts	±50 ft	±100 ft	Holding Radial 1/2 dot	Holding Radial 1 Dot	N/A	N/A

Table A.6: Basic Instrument HQR Summary

		NACELLE AND AIRSPEED CONFIGURATION						
		0^o 200 kts	30^o 150 kts	45^o 130 kts	61^o 110 kts	75^o 80 kts	Transition 75^o - 0^o 80-200 kts	Conversion 0^o - 75^o 200-80 kts
MANEUVER	Level Acceleration						3	
	Level Deceleration							3
	Level Turns	2	2	3	2	3	3	3
	Constant Speed Climbs	2	3	3/5	3	2		
	Constant Speed Descents	3	3	4/5	2	2		
	Climbing Acceleration						4	
	Descending Deceleration							5
	Unusual Attitude Recovery	2	5	2	4	5		

Note: Blocks with two HQRs correspond to ratings given by two pilots of different V-22 flight experience.

VITA

Scott B. Trail was born in Kansas City, Missouri on November 3, 1971. He attended public school in Paola Kansas, graduating from Paola High School in May of 1990. Mr. Trail attended Vanderbilt University in Nashville, Tennessee on a ROTC scholarship, graduating cum laude with a degree in mechanical engineering and minor in materials science in May of 1994. Commissioned a 2nd Lieutenant in the United States Marine Corps, he attended The Basic School in Quantico, Virginia in June 1994 before being accepted for flight school in Pensacola, Florida. Mr. Trail received his Naval pilot wings in October 1996 and was assigned to fly CH-46E Sea Knight helicopters, stationed at Marine Corps Air Station, El Toro, California. After one deployment to the Persian Gulf in 1998 and another deployment to Afghanistan in 2001, Mr. Trail was accepted to Naval Test Pilot School class 124, at Naval Air Station, Patuxent River. Mr. Trail graduated Test Pilot School in December 2003 and is currently assigned to HX-21 as a developmental test pilot for the MV-22B Osprey tiltrotor.

Mr. Trail is a Major in the United States Marine Corps with over 2,300 flight hours in over 15 different aircraft. He has conducted numerous flight tests in the V-22 and is currently the project pilot for the Fast Rope/Hoist, Flight Director/Coupled Modes, Short Takeoff and Landing Performance, and Vehicle Management System (flight control) Software test programs.