Report to the V-22 Blue Ribbon Panel

V-22 Test and Evaluation Issues

Philip E. Coyle
Purpose

- Address factors, as they affect safety and combat effectiveness of the V-22:
  - Suitability to satisfy operational requirements
  - Performance and safety of flight
  - Training
  - Engineering and design
  - Production and quality control
Overview

- Review of Operational Testing of V-22
- OPEVAL Waivers / OPEVAL Test Content
  - Operational Effectiveness
  - Vulnerability
  - Operational Suitability
- Findings from OPEVAL and LFT&E
- Topics of Special Safety Concern
- Recommendations
## Status of Delivered V-22 Aircraft

<table>
<thead>
<tr>
<th>Aircraft Number</th>
<th>Use</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full-Scale Development (FSD)</td>
<td>Storage (1992)</td>
</tr>
<tr>
<td>2</td>
<td>FSD – continued use in early in EMD</td>
<td>LFT&amp;E at China Lake</td>
</tr>
<tr>
<td>3</td>
<td>FSD – continued use in early in EMD</td>
<td>Museum (1996)</td>
</tr>
<tr>
<td>4</td>
<td>FSD – Destroyed in 1992 crash</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>FSD – Destroyed on first flight in 1991</td>
<td>LFT&amp;E at China Lake</td>
</tr>
<tr>
<td>6</td>
<td>FSD- Not fully assembled</td>
<td>LFT&amp;E at China Lake</td>
</tr>
<tr>
<td>7</td>
<td>Engineering and Manufacturing Development (EMD) – then modified to CV-22 configuration</td>
<td>CV-22 testing at Edwards AFB</td>
</tr>
<tr>
<td>8</td>
<td>EMD</td>
<td>Continued use in developmental testing</td>
</tr>
<tr>
<td>9</td>
<td>EMD – then modified to CV-22 configuration</td>
<td>CV-22 testing at Edwards AFB</td>
</tr>
<tr>
<td>10</td>
<td>EMD</td>
<td>Continued use in developmental testing</td>
</tr>
<tr>
<td>11</td>
<td>Low Rate Initial Production (LRIP-1); Used in OPEVAL</td>
<td>VMMT-204 (Marine Medium Tilt-Rotor Squadron)</td>
</tr>
<tr>
<td>12</td>
<td>LRIP-1; Used in OPEVAL</td>
<td>VMMT-204</td>
</tr>
<tr>
<td>13</td>
<td>LRIP-1; Used in OPEVAL</td>
<td>VMMT-204</td>
</tr>
<tr>
<td>14</td>
<td>LRIP-1; Used in OPEVAL; Destroyed in Apr 2000 crash</td>
<td>VMMT-204</td>
</tr>
<tr>
<td>15</td>
<td>LRIP-1; Used in OPEVAL to replace Aircraft 14</td>
<td>VMMT-204</td>
</tr>
<tr>
<td>16</td>
<td>LRIP-1</td>
<td>VMMT-204</td>
</tr>
<tr>
<td>17</td>
<td>LRIP-1</td>
<td>VMMT-204</td>
</tr>
<tr>
<td>18</td>
<td>LRIP-1; Destroyed in Dec 2000 crash</td>
<td>VMMT-204</td>
</tr>
<tr>
<td>19</td>
<td>LRIP-2</td>
<td>VMMT-204</td>
</tr>
<tr>
<td>20</td>
<td>LRIP-2</td>
<td>VMMT-204</td>
</tr>
</tbody>
</table>
Four Periods of Operational Testing (OT) Preceded OPEVAL

- Three earlier test periods, OT-IIA (1994), OTIIB (1995), and OT-IIC (1996), were conducted with aircraft from the earlier Full-Scale Development program
  - Aircraft were approximately 3500 pounds too heavy to meet several JORD mission requirements
  - Provided OT pilots 61 flight-hours experience with operating tilt-rotor aircraft

- OT-IID was conducted in Sep-Oct 98 using final two aircraft (9 and 10) from the EMD program
  - Accumulated 143 flight hours performing operationally relevant tasks
  - Aircraft 10 was maintained by Multi-Service Operational Test Team (MOTT)
Overview of OPEVAL
(Nov 99 - Jul 00)

- Accumulated 844 flight hours on 5 aircraft from first low-rate initial production lot
  - 15 operational pilots
- Included three periods of shipboard testing
- Flew numerous representative mission segments or tasks
- Flew the JORD-specified mission profiles associated with range Key Performance Parameters (KPPs)
Waivers for OPEVAL

- SECNAVINST 5000.2B allows the CNO(N091) to issue "waivers" of two types:
  - From the criteria normally required for entering OPEVAL
  - From the testing requirements in the Test and Evaluation Master Plan
- "Waived items shall not be used in COMOPTEVFOR's analysis to resolve COIs [Critical Operational Issues] ..."
Waivers to Criteria for Entering OPEVAL

- Waivers requested with expectation that JORD thresholds would not be met in OPEVAL for:
  - Reliability (Mean Time Before Failure/MTBF)
  - BIT System False Alarm Rate

<table>
<thead>
<tr>
<th></th>
<th>JORD Threshold</th>
<th>EMD Experience pre-OPEVAL</th>
<th>PM Prediction for OPEVAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF (hrs)</td>
<td>$\geq 1.4$</td>
<td>0.64</td>
<td>1.0</td>
</tr>
<tr>
<td>FA (percent)</td>
<td>$\leq 25$</td>
<td>82</td>
<td>66</td>
</tr>
</tbody>
</table>
## Waivers to Testing Requirements

<table>
<thead>
<tr>
<th></th>
<th>Operational Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Safety</td>
</tr>
<tr>
<td>Inadequate cargo handling and airdrop capability</td>
<td></td>
</tr>
<tr>
<td>Inadequate NBC overpressure protection</td>
<td>●</td>
</tr>
<tr>
<td>Avionics navigation system does not provide datums other than world geodetic system</td>
<td></td>
</tr>
<tr>
<td>Excessive force required to disconnect the intercommunication system</td>
<td>●</td>
</tr>
<tr>
<td>Inadequate NBC overpressure system</td>
<td>●</td>
</tr>
<tr>
<td>Pilot and co-pilot seats incorporate inertial reels from non-qualified parts list</td>
<td></td>
</tr>
<tr>
<td>Inability to carry external loads at night due to incorrect radar altimeter readings</td>
<td></td>
</tr>
</tbody>
</table>
## Waivers to Testing Requirements

<table>
<thead>
<tr>
<th>Operational Impact</th>
<th>Safety</th>
<th>Combat Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar warning receiver provides degraded band 2 angle-of-arrival</td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Lower cabin door not operable in a hover</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Autorotative descent cannot be maintained while attempting engine air start</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Unable to align LWINS (inertial system) without GPS signal</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>No flight allowed in icing conditions</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Aircraft envelope not cleared for Air Combat Maneuvering (ACM)</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>
## Waivers to Testing Requirements

<table>
<thead>
<tr>
<th>Operational Impact</th>
<th>Safety</th>
<th>Combat Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max short-takeoff weight (shipboard) 48,500 lbs vice mission profile specific weight</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>Auxiliary fuel tank not crashworthy</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>Not cleared to refuel from a KC-135 tanker</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>Ground collision and warning system (GCAWS) not available for test</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>No defensive weapon system, i.e., gun</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>Inability to fastrope out of cabin door</td>
<td>•</td>
<td></td>
</tr>
</tbody>
</table>
OPEVAL Testing Was Adequate But Had Limitations

- Impacted by Waivers
- Did not test full shipboard operations
  - Max of 4 MV-22s, with low availability
  - Not tested during integrated ops with other aircraft, but evaluated by OTAs as satisfactory based on analysis
- Did not operate from shipboard “... at night, in low visibility or adverse weather” -- key elements of the “typical Operational Maneuver from the Sea scenario”
  - OPEVAL Flight clearance prohibited flight in Instrument Meteorological Conditions (IMC)
- Conducted numerous representative tasks but few end-to-end missions, particularly:
  - Multi-aircraft missions in landing zone (LZ) area
  - Shipboard operations with other type aircraft
Operational Effectiveness Findings from OPEVAL: OPEVAL Confirmed Performance Advantages of Tilt-rotor

Range
- MV-22 can carry 24 troops 250 nm while the CH-46 is unable to operate to this range

• Speed
  - MV-22 can cruise at 225 knots compared to approximately 100 knots for CH-46

• Payload
  - MV-22 can carry external 10000 lb load to 75 miles while CH-53D limited to about 6600 lbs to 50-mile range
Operational Effectiveness Findings from OPEVAL: Demonstrated Self-Deployment

- Flew 2100 nm with one aerial refueling from California to Maryland
  - In 8 hours, 10 minutes versus JORD threshold of 12 hours
Operational Effectiveness Findings from OPEVAL:
Reduced Exposure

- Impressive capability for rapid en route deceleration for ingress to landing zone (LZ).
  Similarly impressive capability to transition and egress from LZ.

- Increased range and speed implies capability to avoid known enroute threats
OPEVAL Confirmed Operational Effectiveness, but Areas of Concern Remain

- Multi-Aircraft Operations - particularly, amphibious ops in “typical” OMFTS scenario
  - Operations “at night, in limited visibility or adverse weather”
  - Capability to maintain needed shipboard flow, integrated with other type aircraft
  - Multi-aircraft ops near LZ

- Lack of a Personnel Hoist

- Inadequate Strength of Ramp and Cargo Floor
  - OPEVAL aircraft required heavy shoring to carry loads

- Incapable of One-Engine Inoperative Refueling
  - JORD threshold requirement for Special Ops Forces (SOF) only, but would be highly desirable for MV-22
OPEVAL Confirmed Operational Effectiveness, but Areas of Concern Remain

- While analysis indicates that MV-22 meets range KPPs, possible weight increases will reduce those ranges.
- Analysis indicates that the CV-22 will not meet the SOF range requirement of 500 nm, but is still a significant range improvement over the CH-46 or CH-53D.
- While the V-22 meets the JORD hot day/high altitude load requirement, it has reduced load capacity in cold weather:
  - Sharp fall-off below -10 degrees Centigrade.
Performance Recommendations:
Gradually Build and Test Full Operational Effectiveness

- Incorporate waived items as soon as possible
- Gain flight experience in IMC
- Conduct multi-ship assault operations
- Conduct multi-ship assault operations from shipboard
- Conduct multi-ship assault operations integrated with other aircraft operations from shipboard
- Conduct multi-ship assault operations integrated with other aircraft operations from shipboard, “at night in low visibility or adverse weather”
Vulnerability:
Live Fire Test & Evaluation (LFT&E)
Test Adequacy

- LFT&E Program was adequate to assess vulnerability of the V-22
  - In many respects, LFT&E was exemplary
  - LFT used as a design tool
  - 592 shots, mostly at components and subsystems
  - Shots against structurally complete aircraft (Static Test Article)

- Limitations
  - Program received waiver from requirement for full-up, system-level testing
  - Missiles addressed through analysis only
  - Engine bay fire extinguishing system not challenged by ballistic tests
V-22 Vulnerability Reduction Design Features

- Redundant Rudders
- * Redundant, Jamproof Actuation System
- Redundant Flaperon Actuators
- * Run Dry Gear Boxes
- Widely Separated Engines With OEI Capability
- * Ram Resistant Wing Tanks
- Redundant Mechanical and FBW Cockpit Controls
- Interconnecting Driveshaft (OEI Capability)
- Crew Seat Armor
- Ballistic Tolerant Primary Structure
- * Ballistic Tolerant Ballscrew Conversion Actuator
- * Dual Tandem Swash Plate Actuators
- Fuel System (Fire & Explosion)
  - "Dry Bay Fire Protection"
  - Nitrogen Inerted Tanks
  - * Self-Sealing Fuel Tanks
  - * Suction Fuel System
- Flight Control System
  - Three Independent Hydraulic Systems
  - Triplex FBW Flight Controls

* Vulnerability Features Developed or Refined Through LFT&E
Design Features Improve Crashworthiness In Some Scenarios

- Large Mass frames located well away from occupied area
- "Bananascrew" failure mode of propeller blades
- Protected shell maintained around occupied area
- Crashworthy cargo restraint
- Controlled wing failure
- Emergency exits
- Crashworthy fuel system
- Crashworthy seats
- Crew headstrike hazards minimized
- Antiplow structure
- Energy absorbing landing gear
- Designed for controlled ditching & post-ditch flotation
Vulnerability: LFT&E Conclusions

- V-22 provides robust protection against projectile threats
  - Meets explicit vulnerability requirements
  - In some areas, able to tolerate damage from larger projectile threats
- Testing supported design improvements to reduce vulnerabilities
- Some of these design improvements also improve safety (e.g., fire suppression)
- Battle Damage Assessment and Repair (BDAR) is not currently funded
Engineering and Design Recommendations:
To Achieve State-of-the Art Vulnerability

- Safety related:
  - Add fire suppression systems in the main landing gear wheel well and also fuselage under floor
  - Make fuel cells homogeneously self-sealing on all sides to improve ballistic tolerance and crashworthiness
  - Make fuel lines in the cabin area more flexible for crash worthiness

- Sustainability related:
  - Develop repair procedures for common wall between sponson fuel tank and cabin (currently not repairable at "O" level)
  - Complete Battle Damage Assessment and Repair Program to ensure combat sustainability
OPEVAL Showed MV-22 Not Operationally Suitable

- Marginal mission reliability
- Excessive maintenance manpower required
- Inadequate availability
- Inaccurate and incomplete documentation
- Non-useful diagnostics
- Poor interoperability, notably communications
- Shipboard capability to handle multiple MV-22s untested
- Crew / Cabin environment concerns
Operational Suitability Findings from OPEVAL:
“Production Deficiencies”

- Numerous failures and maintenance actions occurred during the first months of OPEVAL that the MOTT considered "production deficiencies"
  - Blade Fold Wing Stow system (Corrected and tested in aircraft 19)
  - Spindle Bearing Expansion Bolts
  - Swashplate Actuator Links
  - Rotorhead Clickstuds
  - Swashplate Grease Seals
  - Sliprings

- DOT&E’s analysis considered all suitability data as well as only data after 22 Feb 00 since most (not all) production deficiencies had been resolved by then
OPEVAL Suitability Data

- R&M improved - but still unsatisfactory

<table>
<thead>
<tr>
<th>Measure</th>
<th>USMC Threshold</th>
<th>H-46 Fleet 1995-1999</th>
<th>OPEVAL Results (pre-post 22 Feb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Flight Hours Between Abort (MFHBA)</td>
<td>&gt; 17.0 hours</td>
<td>39.3 hours</td>
<td>9.4 – 18.0 hours</td>
</tr>
<tr>
<td>Mission Reliability (MR)</td>
<td>85%</td>
<td>93%</td>
<td>73 – 85 %</td>
</tr>
<tr>
<td>Mean Time Between Failure (MTBF)</td>
<td>&gt; 1.4 hours</td>
<td>0.48 hours</td>
<td>0.48 – 0.70 hours</td>
</tr>
<tr>
<td>Mission Capable (MC) Rate</td>
<td>&gt; .82</td>
<td>.79</td>
<td>.36 - .57</td>
</tr>
<tr>
<td>Full Mission Capable (FMC) Rate</td>
<td>&gt; .75</td>
<td>.74</td>
<td>.04 - .31</td>
</tr>
<tr>
<td>Maintenance Man-hours per Flight Hour (MMH/FH)</td>
<td>&lt; 11.0 man-hours</td>
<td>15.8 man-hours</td>
<td>38.9 - 18.6 man-hours</td>
</tr>
</tbody>
</table>
## Operational Suitability Findings from OPEVAL:

### Low MTBF

<table>
<thead>
<tr>
<th></th>
<th>OPEVAL Pre-22 February</th>
<th>OPEVAL Post-22 February</th>
<th>Total for OPEVAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Hours</td>
<td>264.4</td>
<td>540.1</td>
<td>804.5</td>
</tr>
<tr>
<td>All Failures</td>
<td>555</td>
<td>772</td>
<td>1327</td>
</tr>
<tr>
<td>MTBF</td>
<td>0.48</td>
<td>0.70</td>
<td>0.61</td>
</tr>
<tr>
<td>Blade Fold Wing Stow</td>
<td>33</td>
<td>.13</td>
<td>46</td>
</tr>
<tr>
<td>Spindle Bearing</td>
<td>36</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>Expansion Bolts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swashplate Actuator</td>
<td>21</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>Links</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotorhead Clickstuds</td>
<td>11</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Swashplate Grease</td>
<td>9</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Seals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sliprings</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Adjusted Failures</td>
<td>443</td>
<td>746</td>
<td>1189</td>
</tr>
<tr>
<td>(Without production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deficiencies)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted MTBF</td>
<td>0.60</td>
<td>0.72</td>
<td>0.68</td>
</tr>
</tbody>
</table>
### Operational Suitability Findings:
**System Failures were not Trivial**

<table>
<thead>
<tr>
<th>Affected Subsystem</th>
<th>Number of Failures</th>
<th>Failures Related To:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Power System</td>
<td>170</td>
<td>Hydraulic fluid level imbalances</td>
</tr>
<tr>
<td>Drive System</td>
<td>80</td>
<td>Gearbox temperature exceedances</td>
</tr>
<tr>
<td>Proprotor System</td>
<td>76</td>
<td>Sheared pins (23), cracked panels, fairing damage</td>
</tr>
<tr>
<td>Flight Controls</td>
<td>69</td>
<td>Swashplate actuators (27), rudder actuator (1)</td>
</tr>
<tr>
<td>Flight Control Computers</td>
<td>69</td>
<td>Multi-Function Displays (21), Nacelle Interface Unit (7), Flight Control Computers (6)</td>
</tr>
<tr>
<td>Fuel System</td>
<td>61</td>
<td>Fuel leaks, suction pumps (4)</td>
</tr>
<tr>
<td>Wiring</td>
<td>53</td>
<td>Wiring harnesses, brackets worn/broken</td>
</tr>
<tr>
<td>Landing Gear</td>
<td>52</td>
<td>Worn tires (8), Landing gear struts</td>
</tr>
<tr>
<td>Nacelle Assembly</td>
<td>48</td>
<td>Panels, latches, minimark fasteners worn/broken (56)</td>
</tr>
<tr>
<td>Electrical Power</td>
<td>47</td>
<td>Generators (1), Batteries (50)</td>
</tr>
</tbody>
</table>

Excludes “Production deficiencies”
Operational Suitability Findings from OPEVAL:
MTBF Growth Predictions Not Met

Source: Briefing, V-22 Osprey OPEVAL OTRR, chart 40, V-22 PMA, 21 Sept 1999
OPEVAL Maintenance Team

- USMC/USAF personnel performed O-level maintenance
- As compared to other IOT&Es/OPEVALs, the MOTT maintainers had more than usual experience with the aircraft
  - Contractor tech reps were required to fill in gaps in documentation, training
Operational Suitability Findings from OPEVAL:
Excessive MMH/FH

MV-22 Maintenance Manhours per Flight Hour

- Scheduled MMH/FH
- Unscheduled MMH/FH

- H-46 Fleet Average = 15.6
- ORD Objective = 11
- OPEVAL Average = 25.3

Pre-22 February
Post-22 February
Operational Pause
Operational Suitability Findings from OPEVAL:
Low Availability Even with Favorable Partitioning of the Data

- Mission Capable Rate
- Full Mission Capable Rate

<table>
<thead>
<tr>
<th>Period</th>
<th>Mission Capable Rate</th>
<th>Full Mission Capable Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-22 February</td>
<td>35.9%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Post-22 February</td>
<td>57.2%</td>
<td>30.5%</td>
</tr>
<tr>
<td>Post-22 February &amp; No Production Deficiencies</td>
<td>57.8%</td>
<td>30.6%</td>
</tr>
<tr>
<td>Post-22 February &amp; No Supply Delays</td>
<td>65.4%</td>
<td>35.8%</td>
</tr>
</tbody>
</table>

MC Requirement = 80%  
FM C Requirement = 75%
Operational Suitability Findings from OPEVAL:
Inaccurate and Incomplete Documentation

- **NATOPS contained inaccuracies and contradictions**
  - Contained FSD and EMD aircraft data - not relevant to production aircraft
  - Performance charts were inconsistent with actual performance or on-board computers
  - HROD hazard was mentioned, but not emphasized
  - Excessive number of steps for pilots to memorize and execute in an emergency

- **Integrated Electronic Technical Manuals (IETMs)**
  inaccurate, immature, incomplete, unclear
  - Developer estimated IETM was 85% complete
  - Most maintenance procedures had not been validated prior to OPEVAL
  - Missing parts lists, required tools lists, installation drawings, and inspection criteria
  - Lack of detail on troubleshooting procedures dictated a need for developer assistance
Operational Suitability Findings from OPEVAL:
Non-Useful Diagnostics

- Aviation Maintenance Event Ground Station (AMEGS) tedious to use
  - Each download generated up to 800 records
  - Maintainers required to ignore “ghost list” items
  - Was only used to confirm faults reported by pilots/maintainers
  - Not integrated with IETMS or other Navy automated maintenance systems

- Excessive BIT False Alarm Rate
  - Every AMEGS record considered a fault indication
  - Most records were indications of normal operation
Operational Suitability Findings from OPEVAL:
Percent of BIT Alarms that were False Did Not Decrease as Fast as Predicted

V-22 False Alarm Burn Down Plan

Source: Briefing, V-22 Osprey OTRR, chart 45, V-22 PMA, 21 Sep 1999
Operational Suitability Findings from OPEVAL:

Additional Problem Areas

- Communications: Failed to meet needs in SATCOM, anti-jam, and data burst areas

- Shipboard Ops: While routine operations will embark a 12 aircraft squadron, OPEVAL did not test:
  - The ability to embark and employ more than four MV-22s
  - The ability to integrate multi-MV-22s with operations of other aircraft.

- Crew / Cabin environment:
  - Insufficient environmental control
  - Poor situational awareness of cabin personnel due to lack of windows; impacts ability of crew chief to safely clear aircraft
  - The aircraft does not provide handholds in the cabin area
  - Some cockpit displays are poorly placed and difficult to read, e.g., the Vertical Velocity Indicator (VVI)
Operational Suitability Recommendations

- Place emphasis on improving MTBF - while ensuring adequate spares funding in the interim
- Examine required levels of scheduled maintenance and implications for MMH/FH
- Place emphasis on maturing and integrating key maintenance documentation, e.g., Integrated Electronic Technical Manuals (IETMs), and diagnostic capabilities
- Ensure continuing review of all maintenance actions for all V-22 aircraft to track progress and identify potential problem areas
  - Ensure that contractor maintenance activities are fully captured in the data
Topics of Safety Concern

- Key component and subsystem failures
- Vortex ring state
- Uncommanded roll incidents
- Autorotation
- Downwash effects
- Ability to egress aircraft
Key Component and Subsystem Failures
Reasons for Concern

- V-22 is a new technology, highly complex aircraft
- The history of side-by-side rotor aircraft is marked by numerous difficulties
- The reliability of V-22 components has lagged behind expectations
- While the V-22 incorporates several redundancies, these imply numerous interactions between hardware, sensors, computers, and software - all multiple failure paths are likely "unknowable"
- We have observed V-22 failures with potential safety implications - based upon Navy/USMC helicopter experience
Findings from OPEVAL:
Flight Critical Subsystems Failed Frequently - Some with Safety Implications

V-22 OPEVAL
Top 10 Failed Major Subsystems

- Hydraulic Power System: 89
- Drive System: 65, 20
- Proprotor System: 57, 17
- Flight Controls: 55, 36
- Flight Control Computers: 41, 8
- Fuel System: 47, 14
- Wiring: 37, 28
- Landing Gear: 31, 2
- Nacelle Assembly: 22, 5
- Electrical Power: 10, 10

Number of Failures
Excluding "Production Deficiencies"
Findings from OPEVAL:
Typical Flight Critical Subsystem Failures with Safety Implications

<table>
<thead>
<tr>
<th>When Discovered</th>
<th>Subsystem</th>
<th>Discrepancy</th>
<th>Safety Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between flights</td>
<td>Hydraulics</td>
<td>Hydraulic leak in mid-wing area</td>
<td>Fire Hazard</td>
</tr>
<tr>
<td>Between flights</td>
<td>Hydraulics</td>
<td>Hydraulic leak detected after emergency shutdown L/H nacelle. (Shutdown for L/H PRGB failure, no hydraulic failure detected in cockpit)</td>
<td>Fire Hazard</td>
</tr>
<tr>
<td>Between flights</td>
<td>Fuel system</td>
<td>Fuel leak in L/H center wing cove</td>
<td>Fire hazard</td>
</tr>
<tr>
<td>In flight - Abort</td>
<td>Drive system</td>
<td>Oil leaking from mid-wing area</td>
<td>Fire hazard</td>
</tr>
<tr>
<td>Between flights</td>
<td>Flight control computers</td>
<td>R/H nacelle interface unit failed</td>
<td>Potential effect on critical flight software</td>
</tr>
<tr>
<td>Between flights</td>
<td>Wiring</td>
<td>Data bus line on L/H side rubbed through by NIPCU wires. Also clamp is torn up.</td>
<td>Potential effect on critical flight software</td>
</tr>
</tbody>
</table>
Findings from OPEVAL:
Typical Flight Critical Subsystem Failures with Safety Implications

<table>
<thead>
<tr>
<th>When Discovered</th>
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</thead>
<tbody>
<tr>
<td>Between flights</td>
<td>Flight controls</td>
<td>Hydraulic fluid leaking from R/H in-board swashplate actuator</td>
<td>May lead to actuator failure</td>
</tr>
<tr>
<td>Between flights</td>
<td>Flight controls</td>
<td>System #1 pressure line worn through by bolt on wire harness clamp</td>
<td>Loss of redundancy</td>
</tr>
<tr>
<td>Between flights</td>
<td>Flight controls</td>
<td>R/H rudder actuator failed</td>
<td>Reduced controllability</td>
</tr>
<tr>
<td>In flight - Abort</td>
<td>Fuel system</td>
<td>Fuel leaking from R/H feed tank vent in flight. Increases with acceleration or deceleration. Feeds increase to 648 both sides during STO and venting increases</td>
<td>Loss of fuel / compromise of needed mission range</td>
</tr>
<tr>
<td>In flight</td>
<td>Doors</td>
<td>Lower crew door will not open after aircraft goes weight on wheels. Must shut down aircraft and restart in order to disengage door lock pin</td>
<td>Inhibits emergency egress</td>
</tr>
<tr>
<td>In flight</td>
<td>Drive system</td>
<td>L/H prop-rotor gear box posted high temp</td>
<td>Potential of gear box failure if unable to land before runaway overheating</td>
</tr>
<tr>
<td>In flight - abort</td>
<td>Drive system</td>
<td>L/H prop-rotor gear box high temp – eventually high enough for precautionary landing (114 deg C)</td>
<td>Potential of gear box failure if unable to land before runaway overheating</td>
</tr>
</tbody>
</table>
Safety Recommendations: Component and Subsystem Failures

- Identify by analysis all safety critical components, subsystems, and interactions - hardware and software
- Review the qualification and developmental testing conducted in order to determine safety margins and expected failure rates
- Examine primary contributors to risk during "avoid" zone operations for opportunities to reduce failure risk
- Continue actions to flag all potentially safety-related failures and maintenance actions for engineering review
The Need for Further Exploration of the Response of the V-22 to Vortex Ring State
"The April 8, 2000 Class A flight mishap during OPEVAL is attributed to the flight crew entering a high rate of descent at low air speed, and experiencing (but not recognizing) a vortex ring state phenomenon. This condition occurs very rapidly with little or no warning to the pilots."

Joint COMOPTEVFOR/AFOTEC Commander Letter: Operational Evaluation / Operational Assessment (OT-IIE) of the MV-22/CV-22 Osprey, 10 Oct 00
“The V-22 has the potential to enter high rates of descent at high nacelle angles with low airspeed. This condition occurs very rapidly with little to no warning to the pilots. In simulation at 95 degrees nacelle, 39 KCAS, and 0 feet per minute rate of descent (ROD), pulling the thrust control lever (TCL) full aft caused an immediate descent exceeding the 800 feet per minute NATOPS WARNING. If forward TCL is applied at this point, an uncontrolled flight condition is possible. Within 3 seconds, the simulator exhibited in excess of 3,000 fpm ROD.”

Joint COMOPTEVFOR/AFOTEC Commander Letter: Operational Evaluation / Operational Assessment (OT-IIE) of the MV-22/CV-22 Osprey, 10 Oct 00
Continued Testing is Needed

- Little test data or analysis exist on VRS phenomenon

- Navy has begun experiments to try to better understand VRS. While we strongly support these experiments, we recommend:
  
  - The addition of addition of transient conditions with simultaneously increasing power and pitch control input
  
  - The conduct of (planned) testing with multiple V-22s to examine the effect of wakes upon VRS susceptibility
Rotor in Near Vertical Power-On Descent
Rotor in Near Vertical Power-On Descent
Flow Pattern Near Rotor in OGE Hover

Stagnation Surface
(at infinity)

Net Aerodynamic Force

Net Momentum Flow

Hover Downwash Velocity

\[ V_H = T^{1/2} (2\rho A)^{-1/2} \]
"Ideal" Rotor in Vortex Ring State: $V_0 > V_H$

Reduced Net Aerodynamic Force

Reduced Net Momentum Flow
Real Rotor in Vortex Ring State: $V_o > V_H$
Asymmetry and Time Variation Dominate

Net Aerodynamic Force Fluctuates Violently
A Little Forward Airspeed Goes a Long Way

AoA dependence of transition into and out-of VRS is very sharp
A few knots of airspeed will get you in or out
Rate-of-Descent and Pitch Attitude Mix

- Rotor pitch attitude
- $\theta_D$
- $\alpha_D$
- TAS
- RoD
- Glide path angle
- $v_A$
- $v_T$
Navy/Boeing VRS Investigation Test Plan

Axial Component Velocity / $V_H$

Transverse Component Velocity / $V_H$

-0.5
-1.0
-1.5
-2.0
-2.5
0
0.5
1.0
1.5
2.0

0 kts
20 kts
40 kts
60 kts
TR-64 Test Results

- Squares denote SHSS events
- Triangles denote Roll-off events
- Thrust Fluctuation Legend:
  - ≤ 2.5%: ○
  - 2.5% < Thrust < 7.5%: ●
  - Thrust > 7.5%: ◆

- Data points denote Vx/Vz combination at maximum measured thrust fluctuation

- Assumed test data for isolated, low-twist rotor

- Velocities referenced to the rotor disk and non-dimensionalized by momentum-based induced velocity for measured thrust

- Assumed winds based on wind calls prior to event. Actual wind data not yet incorporated.
Effect of Rotor Flow Components on VRS

*** This is a notional diagram, not V-22 data ***

equilibrium flight

Axial Component Velocity / \( V_H \)

Transverse Component Velocity / \( V_H \)

Severe VRS Region

VRS Transition Region

GW=40,000
GW=45,000

Effect of increasing
disc AoA

\[ V_H = T^{1/2} (2\rho A)^{-1/2} \]
RoD Restrictions Need to Cover All Foreseeable Circumstances

**case 1**
- IAS = 40 kts
- RoD = 3,500 ft/min

**case 2**
- IAS = 40 kts
- RoD = 2,000 ft/min

**case 3**
- IAS = 40 kts
- RoD = 500 ft/min

**cockpit**
- 60°
- 40 kts
- 3500 FPM

**rotor**
- $V_T = 20$ kts
- $V_A = 3,500$ ft/min
One Possible Scenario

COCKPIT INDICATIONS:

IAS = 40 kts
GS = 10 kts
RoD = 800 ft/min
Nighthawk 72 Rotor-Flow Geometry

$V_A = 2700 \text{ FPM}$

$V_T = 29 \text{ kts}$

$43^\circ$

$13^\circ$

$60^\circ$

$40 \text{ kts}$

$2050 \text{ FPM}$

(20 kts)
Flying Through the $V_T - V_A$ Plane

Nighthawk 72

Axial Component Velocity / $V_H$

Transverse Component Velocity / $V_H$

roll and yaw commands applied at this point
Handling Characteristics of Side-by-Side Rotors
Right Yaw Command Near VRS Region

Before Command Applied

After Command Applied
Right Yaw Command on the $V_T - V_A$ Plane
Left Roll Command Following Right Yaw

- Right rotor remains in VRS region
- Left rotor remains out of VRS

Graph showing the relationship between Axial Component Velocity / $V_H$ and Transverse Component Velocity / $V_H$. Points R and L indicate the positions of the rotors.
Gust/Wake-Induced Scenario

Left Rotor

Right Rotor

\( \alpha_D \)

\( \alpha_D \)

-\( V_y \)

Gust/Wake Velocity
Factors Affecting $V_T$ & $V_A$ on S-by-S Rotors

- Roll commands (differential collective on R and L rotor)
- Yaw commands (differential cyclic)
- One rotor flying into other aircraft wakes
- One rotor flying into asymmetric self-induced flows (slips, yaw, pedal turns)
- Changing nacelle angle (rotor disk AoA)
- Combinations of any of the above
VRS Conclusions

• The side-by-side rotor configuration of V-22 is susceptible to asymmetric onset of VRS with one-rotor-in/one-rotor-out conditions resulting in large rolling moments and departure from controlled flight.

• Such a characteristic is fundamental and cannot be remedied by minor design changes. Only near-term solution is to restrict operations to avoid proximity to VRS region.

• Restriction on RoD alone will not suffice. Will be necessary to impose quick-stop and related restrictions, restrictions on yaw rates under some conditions and restrictions on proximity to other A/C.

• A VRS proximity warning system can be developed to cue pilots, this may be a significant operational aid, but will be of little value in situations where VRS is entered by rapid control inputs.

• More basic research, supplemented by flight testing, is required to map the VRS envelope of V-22 and understand the consequences of operations near the boundary of this phenomenon.
Operational Restrictions

- **Current Restrictions:**
  - Do not exceed 800 FPM rate of descent anytime with nacelles at or above 80 deg
  - Do not fly within 250 feet of another aircraft anytime with nacelles at or above 80 deg.

- **Additional Restrictions May Be Needed, such as:**
  - During a quick-stop maneuver limit pitch attitude to less than xx degrees and pitch rate to less than xx deg/sec.
  - Maximum allowable yaw rate is xx deg/sec anytime with nacelles at or above 80 deg and airspeed below xx kts.
  - Approach and departure operations in rugged terrain or at-sea with strong winds.
Safety Recommendations:
Vortex Ring State

- Complete the on-going program of High Rate of Descent (HROD) flight tests, adding transient conditions to the planned testing sequences to include simultaneous inputs in the pitch axis
- Conduct testing of interactions with wakes from nearby aircraft
- Examine if additional flight restrictions are needed beyond a rate of descent limitation
- Ensure the flight simulator accurately reflects VRS behavior
Safety Recommendations:
Vortex Ring State

- Ensure that cockpit instrumentation provides adequate situational awareness of VRS susceptibility
- Provide the pilots with unmistakable warning of VRS susceptibility
- Ensure the NATOPS adequately address VRS
- Ensure that the pilot training syllabus emphasizes VRS avoidance and recovery
- Encourage research into VRS
Questions

- If operational restrictions on the flight envelope turn out to be sufficient to resolve the issue, can the USMC do its primary mission with such restrictions?

- If the mission can be done with the imposed restrictions, how common will be the situation where a crew exceeds the limitations?
  - Loss of S/A under stress
  - Emergencies requiring autorotative descents
  - Unusual wind conditions
Uncommanded Roll Incidents
Evidence of Lateral Flight Instability

Prior to OPEVAL - Uncommanded right roll during in-flight refueling in conversion mode and 5-20 feet aft and below KC-130 tanker

Prior to OPEVAL - Lateral instability during shipboard vertical landing resulted in nonlinear roll (37°) response and unanticipated wave off.

20 Feb 00 - MOTT Pilot, "Take Offs are easy but the last 10 feet of a landing requires smooth pilot control. If there is an adverse wind over the deck (one that causes higher than normal deck turbulence levels), it can be difficult to achieve an accurate landing. The point in case was Spot 7 with a Stbd 30 wind of 12 Kts. This characteristic is manifested by a lateral wobble at 7-10' than can develop into a PIO, particularly if the pilot follows the deck."

21 Feb 00 - MOTT Pilot, "Aircraft is squirrely at low hover while attempting to land. Numerous suitability issues"
Evidence of Lateral Flight Instability

28 Mar 00 - Uncommanded right roll (45°) of trail aircraft in formation landing with 150 feet separation.

30 Apr 00 - MOTT Pilot, “The aircraft is somewhat unstable in the lateral axis during waveoff. Pilots who are high gain will have trouble flying this aircraft. Extreme attention must be paid to preventing over-controlling this aircraft in the roll channel.”

30 May 00 - MOTT Pilot, “Still feel that we do not have the best solution for roll channel software coding. More than once we have hit full throw in roll channel and had to wait for input response. Is this lack of processing speed or software?”

8 Jul 00 - Unanticipated left roll (15°) of trail aircraft in formation landing with 400 feet separation.
Autorotation
Background

- Autorotation is the rotary-wing analog of gliding (unpowered flight)

- Autorotation is required for:
  - Dual engine failure
  - Single engine failure while operating outside single engine envelope
  - Drive train failure while operating single engine
  - Rotor component structural failures
  - Emergency (minimum time) descents

- Autorotative landings are routinely practiced in single engine rotorcraft
# Power-Off Performance Comparison

Nominal, Sea Level, STP

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Glide Ratio</th>
<th>Glide Slope (degrees)</th>
<th>Rate-of-Descent (ft/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-707</td>
<td>15.0</td>
<td>3.0</td>
<td>1,200</td>
</tr>
<tr>
<td>V-22/APLN</td>
<td>4.6</td>
<td>12</td>
<td>3,500</td>
</tr>
<tr>
<td>MH-60</td>
<td>4.3</td>
<td>13</td>
<td>2,300</td>
</tr>
<tr>
<td>CH-53D</td>
<td>4.0</td>
<td>13</td>
<td>1,800</td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>3.0</td>
<td>19</td>
<td>12,000</td>
</tr>
<tr>
<td>V-22/VTOL</td>
<td>2.0</td>
<td>26</td>
<td>3,800</td>
</tr>
</tbody>
</table>
Autorotation Energetics

Rotor kinetic energy per unit gross weight

Rotor disk loading, DL - lb ft²

Avoid

- Bell 206
- AH-1
- Bell 412
- UH-60
- CH-53E
- H-300
- H-500E
- AH-64
- S-76A
- R-22
- V-22

Altitude

- Altitude 10
- Altitude 5
- Altitude 20

Specific energy stored in rotor

Dim = St + PE

Max height you can achieve on all energy conversion
Single Engine Height-Velocity Envelope

"...represents the envelope of height above the ground and velocity combinations that result in safe OOI landing."
Dual Engine Height-Velocity Envelope

NOTES
1. Boundary provides target airspeed and minimum altitude following a SECOND engine failure
2. Valid up to 55,000 LB gross weight

"This chart serves to provide target speed and minimum altitude for controllable autorotative descent following an OEI condition"
Autorotation at 60° Nacelle Angle is problematic

Glide path at same angle as proprotor disk plane results in little or no autorotative driving force on rotor.

Excessive loss of rotor RPM with power interruption.
Drive Train Failures and the Need for AR

- Drive shafts
- Shaft support (double bearings)
- Shaft supports (single bearing)
- Conversion spindle
- Propeller gearbox
- Pylon mounted driveshaft

NOTE:
Left side shown. Right side typical.
V-22 Autorotation Testing

  “V-22 DT-IIA Maneuver Limitations”

<table>
<thead>
<tr>
<th>Item</th>
<th>Proposed Operational limit</th>
<th>DT-IIA Limitations</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autorotation</td>
<td>Not Defined</td>
<td>Prohibited</td>
<td>No contractor testing</td>
</tr>
</tbody>
</table>

  - No discussion of autorotation

  - No discussion of autorotation
Autorotation Testing

• “Autorotation testing has not been accomplished yet.”

• “The contractor’s simulation model does not have adequate data to accurately model autorotation.”

• “The lack of proven autorotation capability is cause for concern in tiltrotor aircraft.”

INSURV Ltr. to SECNAV, *Independent Technical Assessment of the Readiness for OT-IIE of the MV-22 Aircraft*, 17 Sep 99
FAA Regulations

- FAA AC 29-2B establishes rules for air worthiness of passenger-carrying rotorcraft:
  - Must demonstrate “ability to transition safely into autorotation after failure of last operative engine”
  - Must demonstrate “a landing from autorotation be possible on a prepared surface.”
  - “The rotorcraft must be capable of conducting the all engine out landing at the takeoff and landing WAT (weight, altitude, temperature) limiting conditions up to the maximum altitude approved for takeoff and landing.”

- While FAA regulations do not apply to military aircraft, the DoD has followed the intent of these aircraft in the developmental testing of previous rotary wing programs
Conclusions

- Traditionally, autorotation is a required air-worthiness capability for military rotorcraft

- High rotor disk loading and low rotor inertia places V-22 well outside the nominal autorotation envelope of existing rotorcraft

- Basic rotorcraft engineering analysis indicates that the V-22 will have a difficult time achieving a stable autorotation following a sudden power failure at high power setting, and that the probability of a successful autorotational landing from a stable autorotative descent is very low.
Safety Recommendations:
Autorotation

- Review the extent of completed and planned analysis, simulation, and flight test of V-22 autorotation capability
- Examine opportunities for, and risks of, further autorotation testing
- Ensure that the flight simulator accurately represents the V-22 autorotation characteristics and include emergency autorotation in pilot training
- Conduct a detailed safety "risk" evaluation of:
  - The frequency of V-22 operation in "avoid" regions and tactical opportunities to reduce that frequency
  - The likelihood of essential component or subsystem failure(s) during flight in "avoid" regions
Downwash Effects
Reasons for Concern

- While operational testing has shown that tactics and procedures can allow several key tasks despite downwash, many tasks remain problematic
  - Personnel rescue from the sea (untested)
  - Use of a rope ladder or three simultaneous fastropers (unlikely)
  - Maintaining an offensive posture during fastrope direct assault missions, e.g., gas or oil platforms, maritime interdiction

- Downwash raises individual and aircraft safety concerns
  - Landing is difficult in desert environment and is extremely difficult at night
  - Crew chief has difficulty visually clearing aircraft for landing - particularly in combination with small cabin windows
  - Potential danger to nearby personnel, other nearby aircraft
  - Large debris can be swept into cabin
V-22 Downwash Exceeds that of Helicopters

  
  “Based on limited data obtained, the MV-22 aircraft has significantly greater flow field depth, velocity magnitudes, and force magnitudes than all Navy and Marine operational helicopters.”
Downwash Effects on Personnel

![Graph showing wind force vs. distance from aircraft center.](image)

- **MV-22 @ 39,500 lbs**
- **CH-53E @ 45,000 lbs**

Downwash Effects on Personnel

Safety Recommendations:
Continued Development of Tactics and Procedures for Addressing Downwash

- Operational testing has shown that troops can load and egress and that external loads can be attached
  - Constant attention will be needed to maintain personal safety
- Further development of tactics and procedures and operational testing is needed to continue exploration of what tasks can (and cannot) be accomplished with reasonable safety
Ability to Egress Aircraft
Egress May Be Dangerously Slow

- JORD requires transport of 24 combat-equipped troops
- Combat equipment may consist of upwards of 60 to 80 pounds of gear - which may not be stored under the seats due to crashworthiness considerations
- Result is a cabin environment cluttered with unsecured gear
- Emergency egress, particularly water egress after ditching, likely to be difficult and slow
- Many passengers commented on the difficulty of rapid egress
- The cockpit door is difficult to operate, posing a threat to the safe emergency evacuation of the crew
- The cabin door is difficult to operate
Summary

- V-22 provides many operational advantages over existing aircraft
- Reliability and maintenance have not met required levels. Lifecycle cost and safety implications
- Further testing and research is needed in tilt rotor air-worthiness
  - Vortex Ring State
  - Auto-rotation
  - Downwash and remote landings on unprepared surfaces
  - Uncommanded roll phenomena
  - Egress timelines, especially in water
- Incorporate lessons learned in training and simulators