

MV-22B OSPREY SHORT TAKEOFF AND MINIMUM RUN-ON LANDING TESTS ABOARD LHD CLASS SHIPS

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ABSTRACT

This paper describes recent ship suitability tests conducted by the V-22 Test Team in March 2008 aboard USS IWO JIMA (LHD 7). This testing encompassed expanding the Short Takeoff (STO) envelopes and developing a new landing technique termed Minimum Run-on Landing (MROL) to extend V-22 shipboard capability beyond Vertical Takeoff and Landing (VTOL) gross weights (GW). The objectives included: initial development of the MROL technique in the shipboard environment; expansion of STO and MROL GW envelopes to 58,000 lb (lb), 10% above the maximum VTOL GW; development of day and night vision goggle STO and MROL wind envelopes to 45 kt headwind and up to 10 kt crosswind; and gathering sufficient data to support analytical tool validation including but not limited to Short Takeoff and Landing Computation (STOLCOMP) software, developed by the Boeing Company, and Generic Tiltrotor software in order to grant day and night vision goggle STO envelopes beyond tested ambient conditions. A total of 3.6 flight hours were flown resulting in eleven STOs and eleven MROLs being conducted. A limited data set was collected due to insufficient time at-sea during this period of shipboard testing. Further testing is planned in order to continue to develop MROL wind and GW envelopes, to expand the current day and night vision goggle STO wind and GW envelope, and to gather additional data in support of STOLCOMP model validation. Although limited data was collected, the V-22 successfully demonstrated shipboard STOs at heavy GWs above VTOL capability aboard LHD 1 class ships. The V-22 also demonstrated that MROLs are a new and safe technique for landing on LHD 1 class ships at an appreciable ground speed across the spectrum of GWs bands.

NOTATION

σ	Ratio of test day density to standard day density
Spot	Landing spot designation on flight deck
WOD	Relative Wind Over Deck, defined in direction in azimuth (0 deg is down the bow) and speed in kt

INTRODUCTION

The tilting-rotor configuration of the V-22 lends itself to the unique capability of rolling takeoffs in a short distance termed "Short Takeoff," enabling the V-22 to takeoff at GWs above maximum vertical takeoff GWs which is limited to 52,600 lb at sea level. Figure 1 shows a STO being conducted aboard a ship. A STO is conducted by tilting the nacelles forward between 15 and 30 deg, releasing the brakes, and applying full power between 3 and 6 seconds. The longitudinal cyclic is adjusted to keep the main landing gear from lifting off before the nose landing gear. At liftoff, a pitch attitude is captured to establish the desired climb out profile.

During the Engineering and Manufacturing Development (EMD) phase of the V-22 program in the late 1990's, landbased STO nacelle angles had been established at 60 deg and 75 deg. An extensive simulation effort was conducted to determine the optimal nacelle angle for the shipboard STO. Pilots noted that takeoff distance was heavily influenced by pilot technique. Changes in TCL application rate



Figure 1
V-22 conducting STO from the ship

could result in an order of magnitude difference in takeoff distance. From this simulator study, a TCL application rate of 4 inches in 3 seconds and nacelle angle of 70 deg was chosen. The nacelle angle was chosen because it provided a good compromise between altitude and airspeed gain after takeoff.

During the first EMD sea trials aboard USS SAIPAN (LHA 2) in 1999, STOs were planned and tested for the aircraft launching from the AV-8 TRAM line, shown in Figure 2. Conducting STOs from the TRAM line was determined to be unacceptable for fleet operations because the forward parking area of

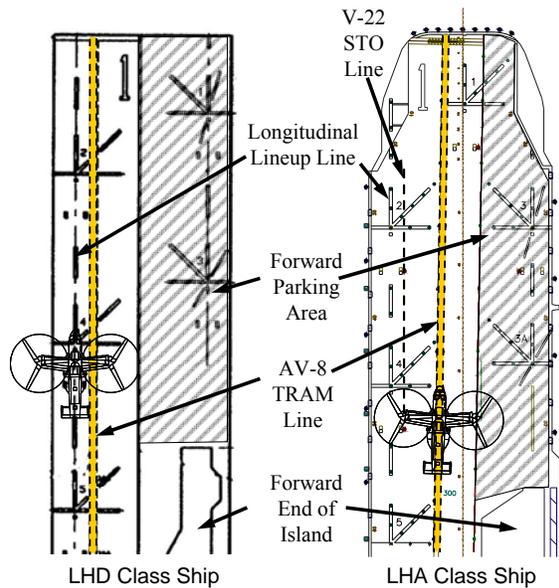


Figure 2

Deck Layout for STO

the ship had to be cleared in order to provide sufficient clearance for the V-22 proprotors. Prior to the second shipboard test aboard USS SAIPAN in 1999, a new V-22 STO line was developed that provided sufficient clearance of the left mainmount with the deck edge and proprotor tips with aircraft in the forward parking area. Similarly on LHD class ships, the longitudinal lineup line of the port side spots was used because it provided greater clearance of the left mainmount to the deck edge than the longitudinal lineup line of the port spots on LHA class ships.

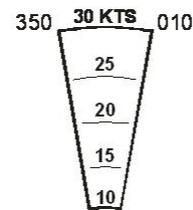
The Operational Requirements Document required shipboard STOs to be conducted up to 57,000 lb in a 15 kt headwind and liftoff within 300 feet. This requirement was an Air Force Special Operations Command requirement to support the self deployment mission. Although it is not specifically stated in any document, it is believed that the Marine Corps

intended vertical launch to be the method for taking off from the ship. However, there was an interest in the STO technique because it was safer due to the aircraft spending less time in the single engine inoperative height-velocity avoid region. Thus, during the second sea trials in August 1999, the V-22 Multi-service Operational Test Team (MOTT) requested an envelope be developed to investigate the benefits of the STO technique. Shipboard STO testing was conducted up to 47,300 lb and supplemented with landbased testing to expand the GW envelope to 50,000 lb. This limited day envelope is shown in Figure 3.

STO

NOTE:

- 1) ENTIRE ENVELOPE - DAY.
- 2) AIRCRAFT SHALL BE POSITIONED ON SPOT 4 TO COMMENCE STO.
- 3) MAX GROSS WEIGHT: 50,000 LBS.
- 4) NACELLE ANGLE: 70 DEG.



DAY PITCH/ROLL: **2 / 3**

Figure 3

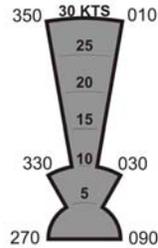
Short Takeoff Wind Limits for LHD/LHA Class Ships

Since 1999, the majority of V-22 shipboard testing has been focused on vertical launch and recovery envelope development and expansion. In November 2004, the day STO envelope was evaluated for night vision goggle operations. No issues were found and the day envelope was approved for night vision goggle operations. Modifications to the flight control laws enabled interim power (109% max torque available) available down to 70 deg nacelle. A nacelle angle of 71 deg was chosen to ensure interim power was enabled during a shipboard STO. Additional analysis using landbased data was conducted to expand the envelope to include calm winds, as shown in Figure 4.

As V-22 aircraft begin deploying on LHD class ships, V-22 squadrons continue to show interest in the capability to conduct shipboard STOs that at a minimum meet the vertical launch capability in GW.

STO

- NOTE**
- ENTIRE ENVELOPE - DAY AND NVG ONLY.
 - AIRCRAFT SHALL BE POSITIONED ON SPOT 4 TO COMMENCE STO.
 - MAX GROSS WEIGHT: 50,000 LBS.
 - NACELLE ANGLE: 71 DEG.



DAY PITCH/ROLL:	2 / 3
NVG PITCH/ROLL:	2 / 3

V-22B STO ENVELOPE

Figure 4
Expanded Short Takeoff Wind Limits for
LHD/LHA Class Ships

The necessity for landing shipboard at GWs above maximum vertical landing GWs was desired by the V-22 test team to increase testing efficiency during STO tests. Without this ability, the aircraft would have to burn fuel or dump water ballast to reduce GW in order to conduct a vertical landing, wasting precious shipboard test time. In June 2005, the No-Hover Landing (NHL) technique was introduced to recover the aircraft to the ship after performing STOs near maximum vertical takeoff GWs for present day conditions. The NHL technique involved using a pre-touchdown flare to arrest forward airspeed while adjusting TCL to maintain glideslope and descent rate. The flare was timed so that forward airspeed was minimized at the point of touchdown. Power was required just before touchdown to help arrest descent rate; however, it was less than what would be required to stabilize in a hover prior to landing. Although pilots liked this technique due to the low workload in the lateral axis, the NHL technique would have limited utility to test above maximum vertical landing GWs due to lack of excess power to arrest descent rate on landing. This testing revealed that the aircraft would have to land with some appreciable ground speed similar to recovery of fixed wing aircraft on aircraft carriers, however, without assistance from ship arresting gear. Neither this class of ship nor the V-22 is outfitted with the equipment necessary for arrested landings. The MROL technique was therefore developed to allow an appreciable ground

speed of less than 20 kt on touchdown and be fully stopped in a minimal amount of distance on the flight deck. Figure 5 shows a MROL being conducted aboard a ship.



Figure 5
V-22 conducting MROL to stern of the ship

This paper will provide an overview of test equipment, test planning and execution, post-test analysis, and test results for the shipboard STO and MROL tests aboard USS IWO JIMA in March 2008.

TEST OVERVIEW

V-22 ship suitability testing was conducted aboard USS IWO JIMA from 4-11 March 2008. The scope of planned STO tests consisted of GW expansion up to 58,000 lb (10% above the maximum VTOL GW), headwind expansion from 0 to 45 kt, crosswind expansion up to +/- 10 kt, and night vision goggle envelope expansion. The scope of planned MROL tests was the same as planned STO tests with the addition of touchdown predictability. Touchdown predictability tests were required prior to conducting other MROL tests to determine the pilot's ability to touchdown within the defined touchdown zone and determine touchdown speeds for safely stopping within the braking zone. A total of 3 flights and 3.6 flight hours were flown during the day. Tests completed included MROL touchdown predictability and STO/MROL GW expansion to 52,000 lb, with partial expansion to 54,000 lb. The limited STO/MROL test productivity was attributed to the sharing of shipboard test time with other ship suitability test priorities, weather delays, and unscheduled maintenance.

TEST EQUIPMENT

Ship: USS IWO JIMA (LHD 7)

USS IWO JIMA belonged to the USS WASP (LHD 1) class and was the follow-on design to the LHA 1 class. This class of amphibious assault ships was 844 feet long, 140 feet wide, had a 26 feet draft, and displaced approximately 40,500 tons fully loaded. Two Combustion Engineering boilers, driving two Westinghouse geared turbine engines, produced nearly 70,000 shaft horse power installed, and propelled each LHD 1 class ship via twin screws to speeds in excess of 22 kt. The flight deck was 819 feet long and 118 feet wide running the length of the ship, approximately 60 feet above the ship's waterline. Aircraft were lowered to and raised from the hangar deck via two elevators, one located on the starboard side aft of the island, and the other located port amidships. The flight deck had nine landing spots with three to starboard and six to port and night vision device compatible lighting. A picture of the ship and the flight deck planform and are provided in Figure 6 and Figure 7.



Figure 6
USS WASP (LHD 1)

Aircraft: MV-22B Osprey

The MV-22B Osprey, built by Bell Helicopter Textron and Boeing Integrated Defense Systems, Rotorcraft System, was a tiltrotor aircraft. The advantage of a tiltrotor design was that the flight envelope encompassed the envelopes of the helicopter and turboprop airplane. The aircraft design consisted of a fuselage with a high wing and twin vertical stabilizers. The fuselage was designed to seat two pilots, two crewmembers, and 24 troops. Twin three-bladed proprotors were located at each end of the wing and were 38.08 feet in diameter. The proprotors were mounted on a gimballed hub, and powered by two Rolls Royce Corporation AE1107C turboshaft engines. Each engine was capable of producing 6150

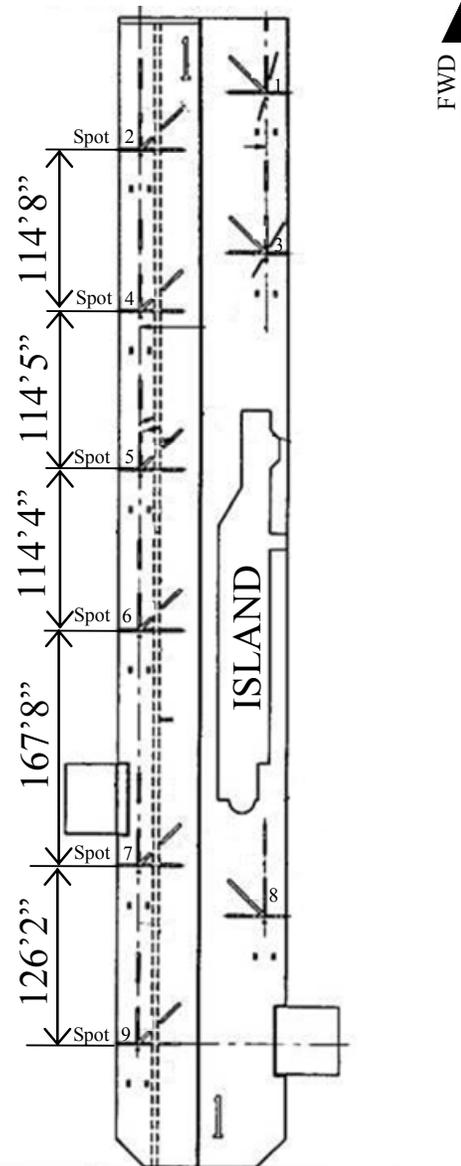


Figure 7
USS WASP (LHD 1) Flight Deck Planform

shaft-horsepower and employed Full Authority Digital Engine Control (FADEC) technology. The nacelle, located at each end of the wing, housed an engine, a proprotor gearbox, and a tilt axis gearbox. The nacelles were designed to rotate about the wing from 0 to 95 deg relative to the aircraft longitudinal axis in order for the proprotors to provide thrust in airplane mode and lift in helicopter mode. In the event of a single engine failure, the proprotors were interconnected via the tilt axis gearbox and the interconnecting drive shaft located in the wing, enabling the transfer of power from the operating engine to the opposite proprotor. The pilots controlled the aircraft via a "fly-by-wire" flight control system.

The flight control system was triple redundant and consisted of the Primary Flight Control System (PFCS) and the Automatic Flight Control System (AFCS). The PFCS provided basic aircraft control, thrust/power management, force feel, and trim control. The AFCS provided full time rate stabilization and selectable attitude stabilization. The Vehicle Management System (VMS) integrated the flight control system with the hydraulic system and enabled the crew to control the aircraft in all modes of flight. The mission computer software controlled avionics and non-avionics subsystems. The aircraft employed a retractable tricycle landing gear. The maximum VTOL GW was 52,600 lb at sea level and maximum shipboard self-deploy GW was 58,000 lb. A water ballast tank was installed in the aircraft in order to achieve the appropriate GW and Center of Gravity (CG) configurations and to provide weight jettisoning capabilities. A photograph and principle dimensions of the MV-22B are provided in Figure 8 and Figure 9.



Figure 8
MV-22B Osprey

The aircraft was outfitted with a Production Aircraft Instrumentation System (PAIS). PAIS was designed as a quickly installable data acquisition system compatible with any V-22 production aircraft. The system was mounted to the seat backs in the cabin and operated by the crew chief. This onboard system consisted of the Common Airborne Instrumentation System (CAIS) Data Acquisition Unit (CDAU), solid state recorder, event counter/marker, Global Positioning System (GPS) synchronized time code generator, telemetry (TM) transmitter, power distribution unit, uninterruptible power supply, and battery. The CDAU acquired data from both avionics data buses, one Flight Control Computer (FCC), event

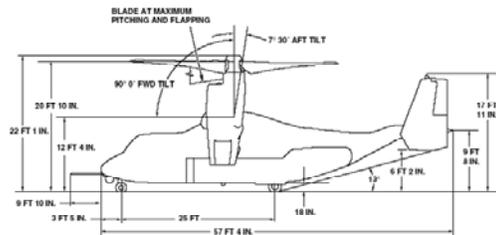
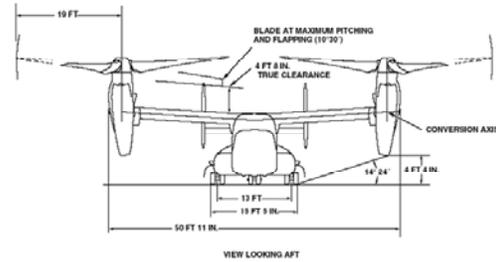


Figure 9
MV-22B in Flight Ready Mode

counter, and the Intercommunication System (ICS) and tagged the data with time. Data were formatted in a pulse code modulated stream and outputted to the TM transmitter and solid state recorder. The solid state recorder recorded data to a removable solid state memory cartridge. Time was maintained and supplied by the GPS synchronized time code generator. At the beginning of each flight, time was synchronized with GPS satellites and maintained throughout the flight by the time code generator. Aircraft data were telemetered back to a ground station. Figure 10 shows a picture of the PAIS.



Figure 10
PAIS

Real-time Telemetry Processing Station

The Real-time Telemetry Processing System (RTPS) provided TM monitoring and postflight data processing and storage capability during shipboard tests and was located within the island of the ship. The RTPS was made up primarily of a series of components manufactured by L3 Communications

and Silicon Graphics Inc. The System 500 (the compilation of these components) was a networked system for data acquisition, processing, storage, distribution (output), and display. It had three major sections of equipment: the color graphics workstation(s); the 550 front end data acquisition, distribution, and storage subsystems; and the local area network connecting front ends and workstations. The System 500 was configured uniquely for each application, with multiple subsystems and color graphics workstations as needed to meet specific system requirements. A System 500 network was configured with a variety of other devices such as external storage units, host computers, and printers. In addition, 4 eight-pin strip charts were run from a total of 32 digital analog converters to support real-time monitoring of aircraft data. The RTPS included two TM receivers, a diversity combiner, and a tracking antenna capable of receiving S-band and L-band frequencies. Recording and playback of the TM signal was performed with a Multi-Application Recording System II tape recorder. Miniature Laser Infrared (MiniLIR) data, as described in the next section, were acquired by RTPS via a fiber optic cable.

Miniature Laser Infrared (MiniLIR)

The MiniLIR was used during testing and was a portable, laser range finding, automatic infrared (IR) tracking system built by SAGEM of France. It provided precision automatic tracking and time space position information (TSPI) data from IR sources. The IR source used for these tests was the aircraft's search light. The basic tracking system consisted of a tracking head, a tripod, two control units, and the interconnecting cables. It was also instrumented with a video camera, a high-speed digital imager, a clock, an eye safe laser ranger, and a GPS antenna. When fitted with the laser ranger, the tracking system provided azimuth, elevation, and range information from a single tracking station. The MiniLIR system provided elevation and azimuth angular data, laser ranging data, time, IR level information, and video to a rack mounted computer control system for video monitoring, data recording and archiving, and data transfer to portable media for data reduction or distribution. The MiniLIR was located on the flight deck at the bow of the ship just starboard of the safe parking line and its corresponding workstation on the ship was located in a workspace at the front of the ship below the flight deck. The MiniLIR was connected to the RTPS station within the island via fiber optic cables. The MiniLIR system is pictured in Figure 11.



Figure 11

MINILIR Laser/Infrared Portable Tracking System

Electro-Optical Tracking System (EOTS)

The Electro-Optical Tracking System was used to obtain Time Space Position Information (TSPI) data and documentary imaging data of these test events. The core of optical tracking was imaging and was used to determine more accurate aircraft lift-off and touchdown points for STO and MROL tests. The data were used in conjunction with MiniLIR data post-event to determine STO and MROL ground roll distances. Fixed, surveyed camera arrays provided TSPI data of a particular target and multi-camera video systems provided documentation of a test event. Three forward cameras were mounted to the island of the ship above the flight deck, which covered spot 5 to the bow of the ship. Three aft cameras were mounted to the island of the ship above the flight deck, which covered landings from spot 7 to the aft end of the ship. All cameras were run at 100 frames per second. High-speed, high-resolution digital imaging systems provided time-tagged high-frame-rate imagery of test events, for engineering analysis and reporting. Video systems provided video routing, display, control, distribution, recording, and editing of live and recorded video sources.

Ship Motion Package (SMP)

The SMP was used to record ship motion and wind condition data during rotary wing ship suitability tests. The SMP consisted of a laptop computer with a GPS antenna for time synchronization and was connected to the ship's computer network. The laptop computer was placed in a workspace within the island and displayed time histories of Wind Over Deck (WOD) speed and direction. In addition, a push button switch was provided to display a 30 second average of WOD speed and direction when it was depressed. Recorded parameters consisted of GPS time, ship course and speed, relative WOD azimuth and speed, ship pitch and roll angles, ship pitch, roll, and yaw rates, and ship surge, sway, and heave accelerations. The SMP is pictured in Figure 12.

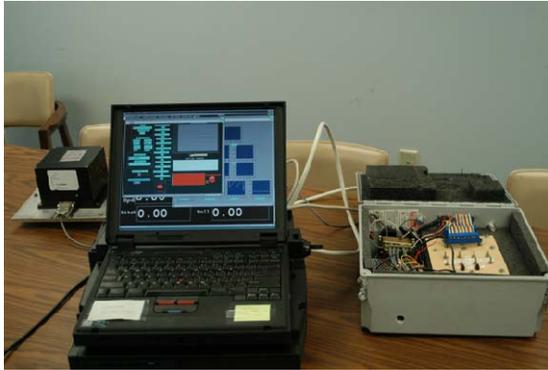


Figure 12
Ship Motion Package

Dynamic Interface Audiovisual Instrumentation System (DAVIS)

DAVIS was used to document shipboard flight test evolutions. The system included four deck or superstructure mounted closed circuit television cameras, of which two were ship's cameras. The camera signals were fed into a quad-splitter, which provided a video output of a selectable single camera or all four cameras simultaneously. A portable scanner unit acquired radio transmissions from both engineers' hand-held radios and aircraft radios. The audio and quad-splitter video outputs were recorded and displayed by an 8-mm video cassette recorder. DAVIS is pictured in Figure 13.



Figure 13
DAVIS

SHIPBOARD METHOD OF TESTS

General

Personnel involved in these shipboard tests included ship suitability engineers, Boeing aerodynamics and flying qualities engineers, aircraft maintainers, aircrew, and instrumentation and telemetry engineers which was approximately 70 people. During underway shipboard testing, the shipboard test coordinator was located in Primary Flight Control within the island of the ship to coordinate test progression with the Air Boss, and

communicated with the bridge engineer located on the bridge of the ship to coordinate WOD conditions. During each flight test sequence, the bridge engineer determined the required ship's course and speed for generating target WOD conditions, and requested the commanding officer or the officer of the deck to maneuver the ship accordingly. After the desired WOD was attained, the test aircraft conducted one or more test evolutions as required. During all V-22 shipboard flight test operations, the test coordinator and TM lead engineer were in direct radio communication with the aircraft. Test team personnel monitored each test sequence and recorded results. For each flight test event (while on deck and following the launch), the pilots transmitted comments by radio which were recorded by test personnel. Each STO and MROL was evaluated using a qualitative assessment called the Deck Interface Pilot Effort Scale (DIPES), as shown in Figure 14, and could have been further quantified with the Cooper-Harper Handling Qualities Rating (HQR) scale. Shipboard flight test communications with the test aircraft were coordinated with the Air Boss or his designated representative. Shipboard communication procedures were briefed before every flight.

Pre-test Simulation

Pre-test piloted simulation was conducted to familiarize the test team with test conduct, to develop test predictions, to refine maneuver procedures, and to practice emergency procedures. Test team familiarization involved conducting test events to get members acquainted with test flow, communication protocol, and knock-it-off criteria and timing. Test predictions were used to determine expected trends and to compare to STOLCOMP. The predictions also aided in determining whether test build-up was sufficient to ensure safe increments in GW and WOD. Although roll on landings had been conducted routinely landbased, the MROL maneuver aboard ship was new and simulation was used to refine this technique. The test team learned that a steeper glideslope was required to ensure more accurate and predictable touchdowns. Also, the pilots developed altitude and Distance Measuring Equipment (DME) checkpoints that aided in maintaining proper glideslope. Through reviewing the test matrix in the simulator, it was apparent that on short final for approach airspeeds less than 30 kt, speed stability was a concern. Pilots deemed maintaining airspeed to be too difficult and resulted in limiting approach airspeeds to no less than 30 kt. Emergency procedures were practiced to familiarize the team in handling an emergency appropriately. In addition, single engine failures were investigated to ensure sufficient wave-

off capabilities. A minimum altitude of 200 feet above ground level (AGL) was chosen to invoke the engine failure. Engine failures at lower altitudes were not investigated due to the close proximity of the flight deck and inability to avoid collision with the ship. At maximum test GW, successful recoveries with a single engine failure were dependent upon water ballast dump.

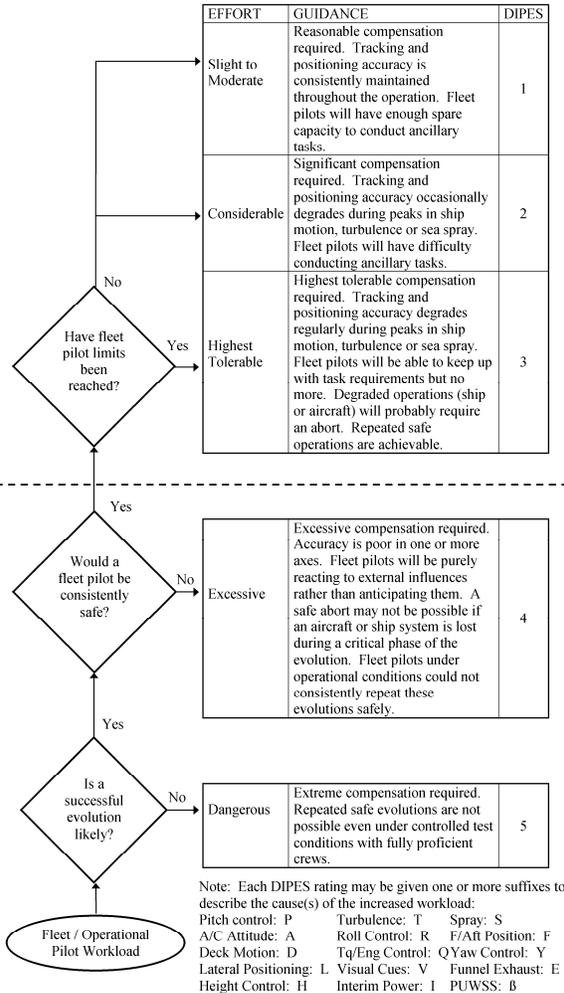


Figure 14
Deck Interface Pilot Effort Scale (DIPES)

Maneuver Procedures

All STOs began with the aircraft positioned on spot 4, and the aircraft rolling along the longitudinal “crow’s foot” lineup line, which provided approximately 208 feet of deck run. An illustration of the deck layout during a STO is provided in Figure 15.

As mentioned previously, the shipboard STO procedures differed from landbased STO procedures. The nacelle angle for shipboard STO was 71 deg and the Thrust Control Lever (TCL) ramp time was 4

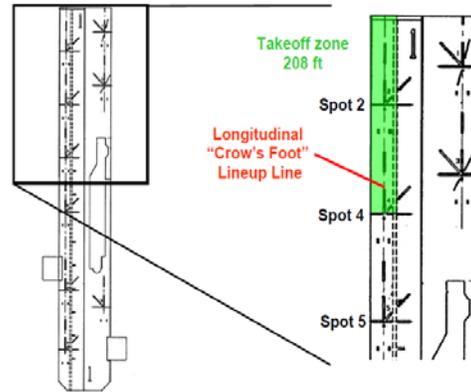


Figure 15
Deck Layout for Short Takeoff

inches in 2-3 seconds vice the landbased ramp time of 6 seconds. STO procedures are described as follows:

- Commence STO on or abeam spot 4
- Nose wheel power steering — OFF
- Nacelles — 71 °
- Interim power ON and 104% Nr
- Set initial longitudinal stick
- Brakes — Release
- TCL — Smoothly apply maximum power (target full application in 2 to 3 seconds)
- At liftoff: capture attitude — 3 to 5 deg nose up

The MROL technique involved the aircraft performing a stern approach to the ship targeting touchdown on spot 9, rolling along the longitudinal “crow’s foot” lineup lines, and fully stopping just prior to the aft end of the island. The touchdown and braking zone is shown in Figure 16. Prior to sea trials, stopping distances were predicted for 15 to 20 kt ground speeds based on STOLCOMP which was validated by landbased test data. Based on these



Figure 16
Deck Layout for Minimum Run-on Landing Technique

predictions, there was sufficient deck space available to stop the aircraft from a 20 kt Touchdown Speed Relative to the Ship (TSRTS). TSRTS is defined as the difference between aircraft ground speed and ship ground speed.

The MROL procedures develop as follows:

- Turn base at 2 nautical miles and 800 feet and begin to slow to 60 nacelle/120 kt indicated airspeed
- Landing checks complete
- Turn final and slow to 50-60 kt indicated air speed at 83-85 deg nacelle
- Intercept glideslope at 1.1 nautical miles
- Maintain a 7 deg glideslope and establish recommended airspeed
- Confirm WOD and Ship's speed over ground to determine landing touchdown speed
- At 0.2 nautical miles rotate nacelles aft 2-3 deg, use longitudinal stick as required to capture touchdown speed
- Prior to crossing the deck edge, transition from indicated airspeed to groundspeed. Target aircraft ground speed was ship's ground speed plus TSRTS as determined from touchdown predictability tests
- Target spot 9 mainmount markings for touchdown
- Maintain 0-5 deg nose up until MLG touchdown
- Reduce TCL to aft stop at touchdown
- Smoothly lower nose wheel to ground
- Apply hard braking
- Adjust nacelle angle to full aft at maximum rate
- Select nose wheel steering when the gear is firmly on the ground if desired
- Terminate maneuver by adjusting nacelles forward to prevent aircraft from rolling aft

STO Envelope Expansion Tests

The planned shipboard STO test points included day GW, headwind, and crosswind expansion, and night envelope expansion. Only day GW expansion tests were conducted and will be the only method of test discussed below.

The first STO test point began within the limits of the previous STO envelope which granted operations up to 50,000 lb GW. Subsequent test points expanded in GW/WOD azimuth/WOD speed relative to either the existing STO envelope or to previously tested conditions. The build-up sequence for STO GW expansion involved increasing GW in 3,000 lb

increments, starting at lighter GWs and building down in winds due to increased power required with wind speed reduction. STO GW expansion tests encompassed four GW bands: 48,000 ± 1,000 lb, 51,000 ± 1,000 lb, 54,000 ± 1,000 lb, and 57,000 ± 1,000 lb. The build-up method involved conducting a test point at a wind condition at a lower GW before conducting the same wind speed condition at the next higher GW band. GWs were not greater than 3,000 lb from previously tested conditions. Each test point was repeated once before proceeding to the next test point to gain confidence that results were repeatable for STOLCOMP validation.

During testing, telemetry engineers were on board the ship monitoring takeoff distance and rate of climb (ROC) so that if trending suggested excessively low deck runs or shallow climbout for the targeted heavier GWs, testing could have been moved aft to spot 5; however, trending showed that all STOs were safe to begin at spot 4.

MROL Envelope Development Tests

The planned shipboard MROL test points included day touchdown predictability; day GW, headwind, and crosswind expansion; and night envelope expansion. Only day touchdown predictability and GW expansion tests were conducted and will be the only method of test discussed below.

MROL testing began with touchdown predictability at a GW band of 48,000 ± 1,000 lb with WOD within the initial envelope and was repeated as required for pilot and test team comfort. The build-up method for MROL touchdown predictability was increasing speeds relative to the ship in 5 kt increments, starting with a target of a 5 kt TSRTS up to the maximum target TSRTS of 20 kt. Results from this test, including touchdown predictability and braking distance, were used to determine a TSRTS that was used for the remaining tests.

Once touchdown predictability tests were completed, MROL GW expansion test points were conducted at the same GW bands as STO tests which were 48,000 ± 1,000 lb, 51,000 ± 1,000 lb, 54,000 ± 1,000 lb, and 57,000 ± 1,000 lb. For each GW band, buildup method included decreasing landing airspeed in 5 kt increments from 10 kt to 0 kt above the all engines operating flyaway airspeed. The all engines operating flyaway airspeed was chosen so that a 400 fpm (fpm) ROC at 85 deg nacelle was achievable. The landing airspeed was limited to no less than 30 kt based on simulation results. The difference in aircraft and ship ground speed was mathematically equivalent

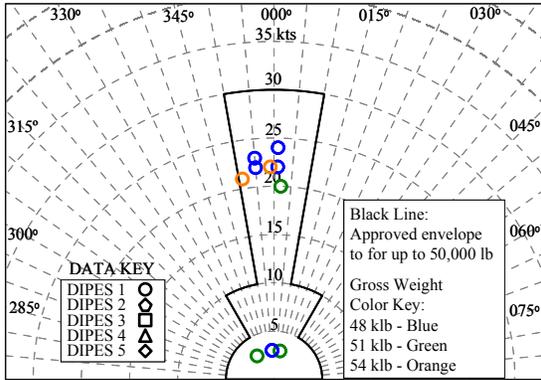


Figure 17
MV-22/LHD 1 STO Data Fairing

to the difference in aircraft and ship wind speed. Thus, ship WOD was determined by subtracting the TSRTS from the aircraft landing airspeed. As an example, if the aircraft landing airspeed was 35 kt and the TSRTS was 15 kt, the WOD would be 20 kt. Each test point was repeated once before proceeding to the next test point to gain confidence that results were repeatable.

All engines operating wave-offs were conducted for each test day prior to the first MROL and any time a heavier GW band was tested to ensure a 400 fpm ROC could be achieved at 85 deg nacelle. All engines operating wave-offs were conducted to provide knowledge of and trending for altitude loss and torque required on trim descent. It also provided pilot proficiency in conducting all engines operating wave-offs. The wave-off was conducted above 500 feet AGL and at an airspeed that was 5 kt greater than the lowest landing airspeed to be tested which ensured the wave-off could be achieved successfully. An altitude to conduct the wave-off of 500 feet AGL was chosen to ensure a safe recovery.

RESULTS

STO Envelope Expansion

A total of 11 STOs were conducted, completing 3 of the 43 planned STO test points including required repeats. Due to limited test time at sea, only STO GW expansion tests were conducted. Table 1 provides a summary of conditions under which tests were completed.

	Minimum	Maximum
GW (lb)	47,224	54,982
Center of Gravity (in)	394.1	396.2
Pressure Altitude (ft)	-441	-92
Outside Air		
Temperature (deg C)	4.3	17.9
Ship Pitch (deg) ^a	-	0.3
Ship Roll (deg) ^a	-	1.0

^aValue is oscillatory maximum.

STOs targeting a WOD condition of 000 deg at 0 kt were conducted up to a GW of 52,119 lb. STOs targeting a WOD condition of 000 deg at 20 kt were conducted up to a GW of 54,982 lb. A data fairing plot of the tested conditions showing the WOD conditions, along with the assigned DIPES ratings and GWs is presented in Figure 17.

Performance

STO test points were evaluated in terms of performance in order to expand the GW STO envelope. Ground roll distances were calculated for each STO. Ground roll distance was considered to be the point where power was first applied to the point where all wheels of the aircraft were off the deck. All ground roll distances were less than 30 feet and ranged from 6.6 feet at WOD conditions of 359 deg at 22 kt to 28.9 feet at WOD conditions of 356 deg at 3

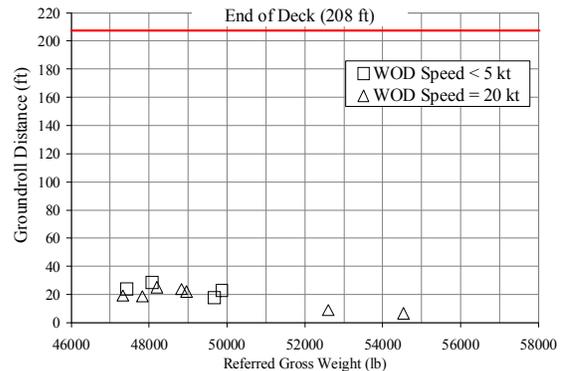


Figure 18
V-22 STO Deck Groundroll Distance
71 deg Nacelle, Fwd CG

kt. A plot of ground roll distances versus referred GW (GW/ σ) for each wind condition can be found in Figure 18. The largest ground roll of 28.9 feet accounted for less than 14% of the total available STO ground roll distance. Note that the shortest ground roll distances were WOD speeds of 20 kt at the heaviest GWs. Liftoff speed relative to the ship as a function of referred GW is shown in Figure 19 below. Liftoff speeds relative to the ship varied from 6 to 13

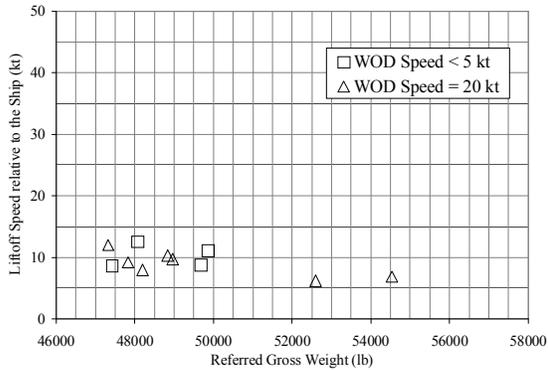


Figure 19
STO Liftoff Speed relative to the Ship
71 deg Nacelle, Fwd CG

kt. Ship headwind conditions did not seem to affect the liftoff speed relative to the ship which indicates that ship airwake effects are minimal. Similar to ground roll distance data, there was no noticeable trend between liftoff speed and GW / WOD. It is believed that pilot technique had a significant effect on the repeatability of liftoff data. The largest contributors to variability could have been TCL ramp time and aircraft pitch attitude on liftoff as these inputs could not be precisely controlled. Due to the small amount of data gathered, trends can not be realized until further testing can be accomplished.

Ground roll distances increased with increasing liftoff ground speed and this trend can be seen in

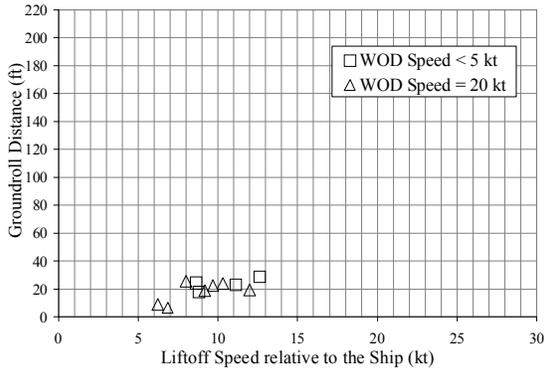


Figure 20
Liftoff Speed Relative to Ship
71 deg Nacelle, Fwd CG

Figure 20. Again, it was difficult to determine the effects that ship WOD had on aircraft acceleration based on the limited amount of data gathered to date.

ROC was monitored throughout the course of the STO but the ROC at the deck edge was of particular interest. As shown in Figure 21 below, all test points with referred GWs between 47,000 and 49,000 lb,

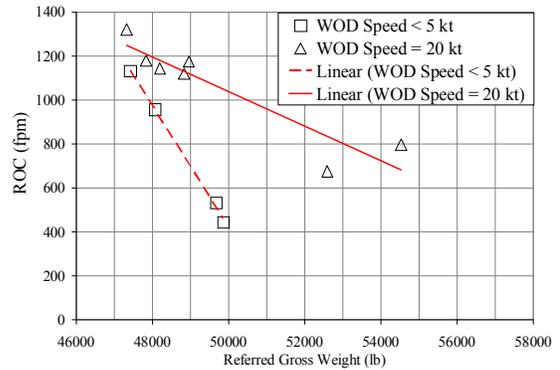


Figure 21
Rate of Climb at Deck Edge
71 deg Nacelle, Fwd CG

regardless of WOD speeds, had a ROC near or greater than 1,000 fpm at the deck edge. Note that a linear trend existed between ROC at deck edge and referred GW for each WOD speed. ROC decreased with increasing GW. The data showed a much steeper drop off in ROC at deck edge for the less than 5 kt WOD speed. For WOD speeds of less than 5 kt, the data indicated that a ROC of greater than 100 fpm at deck edge may not be achievable for referred GWs greater than 52,000 lb. Aircraft pitch angles at the deck edge ranged from -0.4 deg to 3.4 deg, with an average pitch angle closer to approximately one deg. If the pilots were to capture pitch angles closer to 5 deg at deck edge, the ROC would substantially increase and the potential would exist to expand the envelope to referred GWs greater than 52,000 lb.

Due to the limited amount of test data collected, generating an envelope based on what was tested would have limited STO operations to 4 deg C with less than 3 kt of headwind and 27 deg C with 22 to 25 kt of headwind with a linear variation of temperature with headwind between 3 and 22 kt, as seen in Figure 22. STOLCOMP was therefore used to predict results beyond the ambient conditions tested in order to provide an expanded GW STO envelope. There were certain limitations of STOLCOMP including: no presence of a ship airwake model, a two-dimensional flight path, and the inability to model independent longitudinal rotor controls which reduced confidence in predictions and played a role in how much of an expanded envelope could be recommended. In an effort to provide an interim capability for fleet training and preparation for shipboard deployment, flight test data were reevaluated to determine if expansion was possible for 10 to 30 kt of headwind up to 30 deg C up to a GW of 52,000 lb. These headwind and temperature limits were chosen based on the amount of landbased data present, as shown in Figure 22.

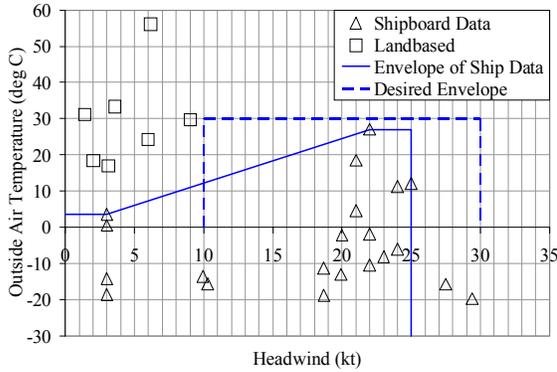


Figure 22

STO Envelope Based on Shipboard and Landbased Data

Shipboard test data were not gathered at 52,000 lb for headwinds below 20 kt up to 30 deg C. Landbased data were gathered beyond GW/σ of 54,700 lb at low headwinds which is equivalent to a GW of 52,000 lb at sea level and 30 deg C. In addition to headwind and outside air temperature (OAT) constraints in making a recommended envelope, ground roll

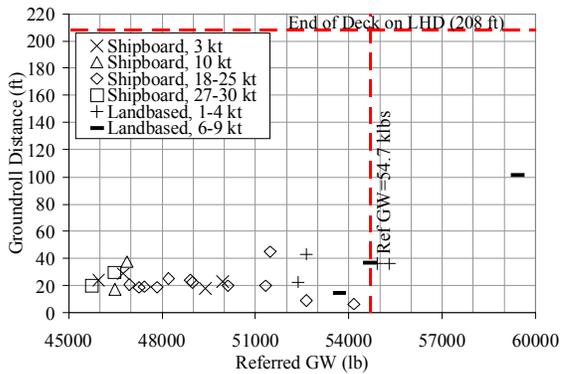
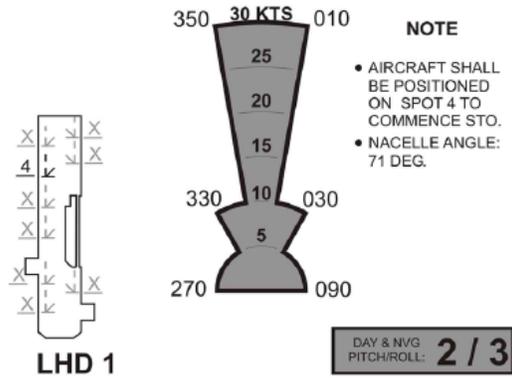
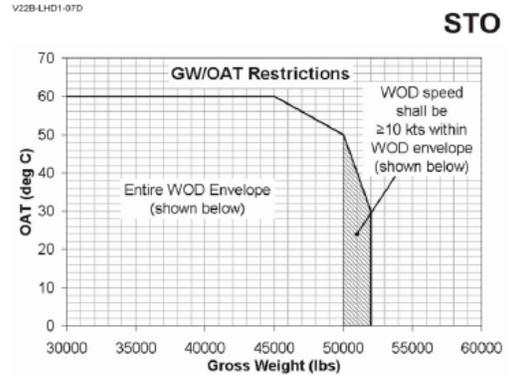


Figure 23

Landbased and Shipboard STO Performance 71 deg Nacelle

distance data were also considered. Ground roll distance as a function of referred GW at different headwind ranges for shipboard and land-based test data are plotted in Figure 23. Notice that ground roll distances were less than 45 feet for GW/σ up to 55,200 lb. Even though land-based STO data did not account for the partial ground effect in the shipboard environment, the expanded STO envelope that was granted to the fleet was limited to no lower than 10 kt headwind at GWs greater than 50,000 lb and up to 52,000 lb. In addition, data showed that ground roll margins of over 300% on LHD class ships existed. Based on these analyses, sufficient deck run was available to conduct V-22 STO operations aboard LHD 1 class ships with headwinds 10-30 kt for GWs up to 52,000 lb and 30 deg C. The recommended



V-22B STO ENVELOPE

Figure 24

V-22 STO Envelope Aboard LHD Class Ships

envelope is shown in Figure 24. Note the 10 kt wind limitation for GWs ranging from 50,000 to 52,000 lb is displayed in the note on the GW/OAT restrictions plot.

Handling Qualities

Day STO handling qualities were also evaluated to grant a day/night vision goggle WOD envelope for the expanded GW envelope. Shipboard STO data were analyzed mainly to ensure adequate control margins, but also to examine for presence of any oscillatory behavior. All STOs were rated as DIPES 1 as shown in Figure 17, indicating minimum effort was required to conduct the maneuver. There was no adverse oscillatory behavior observed during the course of STO testing. The largest handling qualities impact according to the pilots was a slight directional workload on lift-off. Pilots also noted minimal deck rolls and good climb performance and commented, that overall, it was a benign maneuver. Several STOs encountered slight wheelbarrowing effects during the ground roll and nose tucking immediately after lift-off. Wheelbarrowing is characterized by mainmounts lifting off prior to nosewheel lift-off during the ground roll and nose tucking is characterized by the aircraft

pitching down just after lift-off. Two of these STOs were further analyzed for potentially exceeding the aft longitudinal control margin criteria to counter the nose tuck on lift-off; however, it was found later that this large longitudinal input was transient in nature, did not actually exceed the criteria, and was not a concern. There were found to be no flying quality limitations to the STO conditions flown during this test period.

Although night vision goggle STOs were not conducted during this shipboard test, giving a night vision goggle capability was desired. Thus, previous STO test results for both day/night vision goggle were reviewed to validate the recommended night vision goggle STO envelope which was the same as the recommended day STO envelope, as shown in Figure 24. Night vision goggle STOs were conducted up to 47,816 lb GW aboard USS WASP in November 2004 and all were rated as DIPES 1, except one which was rated as a DIPES 2 [1]. WOD conditions for the DIPES 2 night vision goggle STO were 345 deg at 28 kt (7 kt crosswind) and pilots commented that there was noticeable lateral/directional compensation required. The crosswind present in this DIPES 2 night vision goggle STO may have contributed to the additional lateral/directional compensation and increased workload required by the pilots. Another STO was conducted at WOD conditions of 349 deg at 29 kt (5 kt crosswind) and it was rated as a DIPES 1, but pilots also commented on some lateral compensation that was required. The recommended expanded envelope only granted up to +/- 5 kt crosswind, thus the night vision goggle STO envelope which has the same limits as the recommended day STO envelope was granted to the fleet.

Additionally, the effects of GW on the handling qualities were analyzed. Three STOs, which were all at headwinds of 20 kt, were evaluated to determine the effects of increased GW on aircraft handling qualities. The GWs of the three STOs were 47,224 lb, 51,043 lb, and 54,982 lb. The WOD direction for each STO was 355 deg, 002 deg, and 351 deg, respectively. All three STOs showed low amplitude inputs in the lateral and directional axes. Control inputs in the longitudinal axis were of moderate amplitude. It appeared that there was an initial input aft to counter the wheelbarrowing tendency and then approximately a 2.5 to 3 inches forward stick input to keep the pitch attitude less than 5 deg noseup. For the two lighter GW STOs, pilots commented on a small wheelbarrow tendency and minor control inputs. For the STO at a GW of 54,982 lb, pilots commented that there was no wheelbarrowing and it was low workload. All three STOs were rated as a DIPES 1. Therefore, GW was determined to have a negligible effect on STO

handling qualities and it was deemed safe to grant an envelope of +/- 10 deg of the bow out to 30 kt WOD for GWs up to 52,000 lb.

Ship Motion

Since the most ship pitch/roll experienced during the day STO testing was 0.3 deg and 1 deg respectively, additional analysis was conducted to be able to grant the previous STO ship motion limits of +/- 2 deg pitch and +/- 3 deg roll for the recommended GW envelope.

A performance analysis was conducted to determine additional ground roll distance required during a STO which occurred at the maximum ship pitch limit of 2 deg. Analysis of land-based STOLCOMP takeoff and static surface pitch calculations showed that at 52,000 lb, 35 deg C day, headwind of 25 kt, takeoff distance increased by approximately 0.5 feet/deg of surface pitch. At these conditions, takeoff distances were approximately 30 feet. Thus, assuming the 2 deg ship pitch limit, the ground roll distance would increase by approximately 3%. STOLCOMP analysis showed that for 55,000 lb at 35 deg C and a headwind of 25 kt, takeoff distance increased by approximately 4 feet/deg of surface pitch. At these conditions, takeoff distances were approximately 50 feet. Thus, assuming the 2 deg ship pitch limit, the ground roll distance would increase by approximately 16%. The increase in ground roll due to ship pitch was calculated using the slope correction formula from a test pilot school flight test manual for land-based takeoff performance with the assumption that a 2 deg slope remained constant throughout the STO ground roll [2]. Land-based flight test data were evaluated to determine the effect of ship pitch on ground roll. A land-based STO was conducted at a GW of 52,725 lb with a pressure altitude of 23 feet and OAT of 23.9 deg C and resulted in a ground roll of 36 feet and takeoff velocity of 14 kt. The ground roll distance increase due to a 2 deg slope was approximately 6.3 feet, which accounted for a 17.5% increase in ground roll.

From a handling qualities perspective, the proposed ship motion limits were the same as what was recommended from previous tests conducted at lighter GWs. Previous tests conducted aboard USS SAIPAN (LHA 2) resulted in recommendations for ship motion limits of pitch +/- 1 deg and roll +/- 3 deg. Tests conducted aboard USS WASP (LHD 1) resulted in recommendations that increased ship pitch motion limits to +/- 2 deg. For tests conducted aboard USS SAIPAN (LHA 2), pilot ratings showed that little effort was required. STO tests aboard USS WASP (LHD 1) were considered benign. Due to the small

ship motion limits being proposed and the benign handling qualities encountered at light GWs, it was not expected that unacceptable handling qualities would be encountered at GWs up to 52,000 lb.

Based on the previous test data and analysis provided, safe STO operations could be accomplished aboard LHD 1 class ships with ship pitch limits of +/- 2 deg and ship roll limits of +/- 3 deg. The recommended STO envelopes aboard LHD 1 class ships restricted ship pitch limits to +/- 2 deg and ship roll limits to +/- 3 deg, as shown in Figure 24.

MROL Envelope Expansion

A total of 11 MROLs were conducted completing 6 of the 52 planned MROL test points with required repeats. Due to limited test time at sea, only MROL touchdown predictability and GW expansion tests were conducted. Table 2 provides a summary of conditions under which tests were completed.

	Minimum	Maximum
GW (lb)	47,008	53,959
Center of Gravity (in)	394.2	396.3
Pressure Altitude (ft)	-441	-92
Outside Air Temperature (deg C)	4.3	18.0
Ship Pitch (deg) ^a	-	0.4
Ship Roll (deg) ^a	-	1.2

^aValue is oscillatory maximum.

A data fairing plot, showing the WOD conditions, along with the assigned DIPES ratings and GWs, is shown in Figure 25. Note that all MROLs were rated as DIPES 1 or 2. Both performance and handling qualities aspects of MROLs were evaluated to determine suitability of this landing technique for the heavy GW shipboard landing.

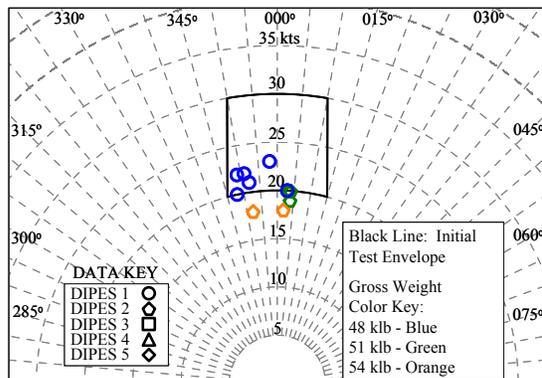


Figure 25
MROL Data Fairing

Performance

MROL testing began with touchdown predictability to determine the pilot's ability to touchdown within the touchdown zone and determine what the appropriate touchdown speed relative to the ship (TSRTS) would be to safely stop within the braking zone. Figure 26 presents stopping distance as a function of TSRTS for both touchdown predictability tests as well as GW expansion. Note that touchdown predictability test points for TSRTS from 12 to 15 kt resulted in stopping distances from 89 to 121 feet. Although there is some variability in the stopping distance based on TSRTS, it was determined that 15 kt was the appropriate TSRTS to

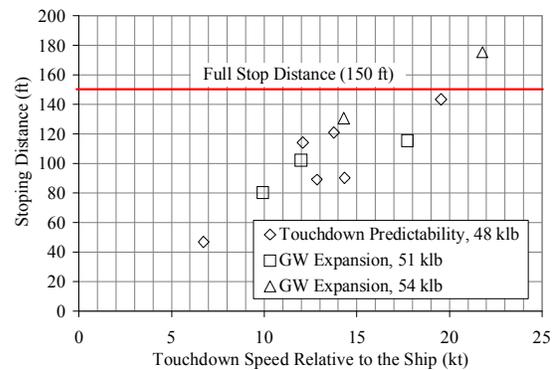


Figure 26
MROL Stopping Distance Performance

allow a safe stopping distance and provide some margin of safety for variability in touchdown speed. Test results demonstrated that MROL ground roll distances with TSRTS up to 22 kt could be achieved with the flight deck space available aft of the island. The touchdown positions relative to the target touchdown point are presented in Figure 27. Aside from the one outlier, pilots were able to accurately land the aircraft within the touchdown zone. The average touchdown position was approximately 9.3 feet beyond and 0.3 to the left of the target touchdown point. Based on this data, the probability of landing longitudinally within +/-25 feet of the spot 9 mainmount markings was greater than 99 %. The probability of landing laterally within +/-3 feet of the spot 9 mainmount markings was greater than 99 %. From this data, there was high confidence that pilots would be able to accurately place the aircraft within the touchdown zone.

GW expansion tests continued using the TSRTS of 15 kt. Note on Figure 26 that the increased GW did not change the stopping distance required for a given TSRTS. As stated in the method of test, the torque on approach was monitored to ensure sufficient excess power was available to arrest rate of descent and

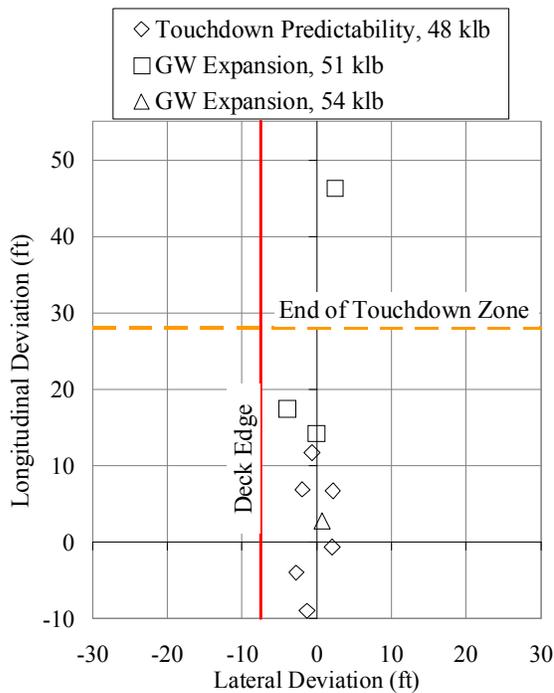


Figure 27
MROL Touchdown Positions Relative to Target Touchdown Point

waveoff on the approach. The peak torque required on approach was plotted against referred GW as shown in Figure 28. Even at the highest GW tested, a 33 % torque margin was maintained throughout the approach. Based on the GWs tested, the minimum WOD speed of 20 kt allowed MROL with sufficient power margin.

Handling Qualities

Throughout the touchdown predictability and GW expansion tests, pilots evaluated the handling qualities of the aircraft using DIPES. Pilots noted the largest workload was in the lateral axis, getting lined up with

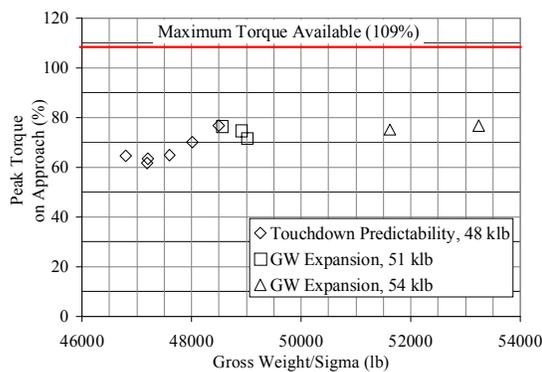


Figure 28
MROL Peak Torque on Approach

the ship on short final. The general pilot sentiment was that MROLs were a benign maneuver for the GWs tested. In addition, the pilots commented that maintaining ground speed relative to the ship during a MROL actually created an easier approach than attempting to decelerate to a hover, reducing lateral workload as the aircraft crossed the deck edge. The MROL technique was validated in the shipboard environment.

CONCLUDING REMARKS

This paper has provided an overview of the test methodology used in order to conduct V-22 sea trials in support of increased shipboard STO capabilities for the fleet [3]. The objectives of this test were partially met. The STO GW envelope was expanded, although not to the fullest extent of the aircraft capability due to insufficient time at-sea. MROL demonstrated to be a revolutionary and safe way to land aboard ship at GWs heavier than VTOL capability and will continue to be developed and tested. An MROL envelope was not recommended due to insufficient test data; however when more can be gathered, the possibility of granting an envelope to the fleet exists.

Further testing has been recommended to continue expansion of the day/night vision goggle STO envelope aboard LHD 1 class ship up to a GW of 58,000 lb for headwinds 0-45 kt and crosswinds of up to +/- 10 kt. It has also been recommended to conduct further testing to gather required data to validate the STOLCOMP model in order to extrapolate beyond tested ambient conditions. Future testing will also involve investigating the MROL technique for GWs up to 58,000 lb along with similar headwind and crosswind limitations.

STO and MROL GW and wind envelopes are currently still under development for LHD 1 class ships but have made significant progress in terms of providing additional capabilities to the fleet. Although future testing has been recommended and is desired, the limited number of amphibious assault class ships and numerous operational commitments poses a challenge to completing these types of shipboard tests. Until more accurate modeling and simulation tools become available to support shipboard envelope development, full scale sea trials, although costly and time intensive, will continue to be the way forward in granting increased shipboard capabilities to the fleet.

ACKNOWLEDGEMENTS

The support from the crew of the USS IWO JIMA is greatly appreciated and acknowledged. The efforts

of the V-22 test team, along with Boeing Flying Qualities and Aerodynamics personnel, were invaluable in accomplishing this testing.

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