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Abstract

The aerodynamic development of the V-22 "Osprey" Tilt Rotor by the Bell-Boeing team is described in this paper. Operational constraints and design requirements to meet future threats impose a significant challenge on the V-22 aerodynamic configuration. A comprehensive program of wind tunnel testing, flight simulation and use of mockups was established to acquire the information necessary to understand the tradeoffs necessary to make proper design decisions while reducing overall program risk. The aerodynamic development of the major components including rotor, wing, fuselage/sponson, empennage and engine inlets are discussed, along with the aerodynamic characteristics based on extensive testing and test/theory correlation. A summary of the V-22 performance is then presented.

Notation

Symbols used in this paper are in accordance with standard notation used in the fixed wing and the rotary wing aircraft industry and are generally defined where used in the text or figures.

1. Introduction

The V-22 Osprey is a multiservice, multimission tilt rotor aircraft suitable for military missions and commercial roles and uses advanced but mature technology in providing this capability. It is designed to takeoff and land like a helicopter and fly like a turboprop airplane - reaching high speeds and high altitudes and possessing long range capabilities. Significant increases in performance are obtained with a short rolling takeoff using partially tilted nacelles. These unique flight characteristics are possible because the pilot can control the direction of the thrust vector by tilting the nacelles. The large wingtip mounted rotors can be tilted through more than 90 degrees, hence the name tilt rotor. An artists impression of the V-22 is shown in Figure 1. The V-22 is currently in full scale development with first flight scheduled for mid 1988. The joint services nature of this program ensures that all four U. S. military branches as well as civilian air transportation will benefit from the tilt rotor's unique capabilities. The operational constraints and unique service requirements impose a significant challenge to the aerodynamic development of the aircraft. The V-22 program will dramatically alter the rotary wing industry as we know it today.

2. Evolution

The V-22 program is the culmination of over 30 years of prototype and technology development which ranged from the Bell XV-3 tilt rotor and the Boeing Vertol VZ-2 tilt wing of the 1950's to the successful demonstration of an advanced mature tilt rotor technology demonstrator embodied by the Bell XV-15 starting in the late 1960's and continuing to the present. The Marine Corps began evolving the operational concept of vertical envelopment shortly after World War II to provide a highly mobile and flexible force for the assault role and subsequent operations on shore. Their efforts -- dedicated ships carrying advanced V/STOL aircraft -- has evolved into a highly effective force. Additional historical perspective is presented in Reference 1.

Over the years various V/STOL aircraft concepts have been studied to understand their effectiveness compared to the conventional and aging helicopters in current USMC/USN inventory (CH-46, CH-53A/D's). With the development of the highly successful XV-15 flight test and demonstration program, the potential of the tilt rotor was realized and the V-22 program was launched. Figure 2 displays this evolutionary process.

In December 1981, the Defense Department identified the tilt rotor as a possible candidate to meet the Marine Corps' new aircraft needs and initiated the V-22 program (originally called JVX). In June of 1982, a Joint Technology Assessment Group determined that the tilt rotor had potential to meet the needs of all four services and a memorandum of understanding was completed among the services by December. The missions identified included Marine medium assault transport, Navy/Air Force combat rescue, Army cargo and medical evacuation and Air Force special operations; all of which benefit from the tilt rotor's speed and range capability. The U. S. Navy is the executive service for this development. To take advantage of this emerging requirement, a team consisting of Bell Helicopter Textron and Boeing Vertol was formed in April of 1982.

3. Program Schedule

Figure 3 shows the overall program schedule. In April of 1983, the V-22 development program was initiated by a preliminary design contract to the Bell-Boeing team. The Preliminary Design Phase was structured to reduce overall program risk through an agressive program of detailed trade studies supported by extensive wind tunnel tests, piloted simulation, the investigation of material properties and structural characteristics, mockups of critical components and analysis of those areas of design peculiar to a tilt rotor aircraft. An important element of this phase was the strong early emphasis on systems engineering and integrated logistics system analyses in support of the air vehicle design. It was during this phase that the aerodynamic configuration was developed. The full scale development proposal was submitted in February of 1985 and June 1985 saw the Bell-Boeing team moving into full scale development of the first prototype aircraft. This phase of development will produce six flight test vehicles and over 4000 hours of development and operational testing after first flight which is scheduled for mid 1988. First production deliveries to the Marine Corps are scheduled for late 1991.

The basic V-22 program will produce 913 aircraft for four services - 552 for the Marines for combat assault and assault support, 50 for the Navy for combat search and rescue, 80 to the Air Force for special operations and 231 to the Army for its many missions. Additional applications are already under consideration, including anti-submarine and electronic warfare applications for the Navy and Marine Corps. Boeing and Bell share the responsibility for the development of the V-22. Boeing Vertol is responsible for developing the empennage, overwing fairings, fuselage and avionics integration. Bell is responsible for the wings, nacelles, transmissions, rotor and hub assemblies and integration of government furnished engines. Other Boeing participation includes Boeing Commercial Airplane Company (BCAC) for the composite wing, Boeing Military Airplane Company (BMAC) for the avionics preliminary design and Boeing Aerospace Company (BAC) for new mission equipment. Allison Division of General Motors is developing and supplying the engines. Grumman Aircraft will build the empennage and Lockheed the wing trailing edge flaps. In addition to these major subcontractors, there is substantial other subcontractor involvement in the program.

4. Configuration Description

Figure 4 shows some of the V-22's salient design features and dimensions. Two 38 foot diameter gimbaled rotor systems and engine/transmission nacelles are mounted on each wing tip, and are powered by two 6150 shaft horsepower Allison T406-AD-400 engines (one per nacelle). The aircraft operates as a helicopter when taking off and landing vertically. Once airborne the nacelles are rotated 90 degrees forward which converts the aircraft into a turboprop airplane. The rotors are synchronized by means of an interconnect shaft that runs through the wing between the nacelle mounted transmissions. This shaft also provides power transmission from one rotor system to the other in the event of engine failure. Auxillary drives from a center wing gearbox provide power for hydraulics, oil cooler and electrical generators. An APU drives through the center gearbox for engine starting.

The aircraft folds compactly for stowage aboard ship. This is accomplished by folding the rotor blades inboard above the wing with the nacelles at 90 degrees (hover). The nacelles are then rotated to cruise position (0 degrees) and the wing is swiveled over the fuselage. Figure 5 illustrates this process.

The V-22 uses an advanced digital fly-by-wire control system. In hover, pitch control is provided by longitudinal cyclic pitch of both rotors. Yaw control is obtained with differential longitudinal cyclic and roll control is obtained by differential collective pitch in each rotor. The aircraft is able to maintain a relatively level roll attitude in sidewards flight by programming lateral cyclic pitch in the same direction in both rotors in addition to differential collective pitch. In the airplane mode, the V-22 is controlled using conventional aerodynamic surfaces - flaperons for roll control, elevators and rudders on the empennage for pitch, turn coordination and crosswind capability. In the transition mode the helicopter and airplane controls are phased for optimum control response.

The V-22 is almost completely constructed of composite materials and has crashworthy seating for 24 combat troops, two external cargo hooks of 10000 lb capacity each for carriage of outsized equipment, a rescue hoist, and a cargo winch and pulley system for loading and unloading heavy internal cargo loads through the aft loading ramp which also permits quick egress and exit of troops. The Osprey is capable of all weather instrument flight, day or night, and continuous operation in moderate icing conditions at weights up to 60500 lb for self deployment.

5. Design Drivers

The design requirements which most influence the aerodynamic configuration of the V-22 are shown in Figure 6. The design is heavily driven by shipboard compatability and spotting on the flight and hanger decks of LPH's, LHA's and LHD's which imposes requirements for wing and rotor folding as well as limitations on maximum length, width and height. The rotor folding requirement limits the number of rotor blades. Maximum hangar deck height on the LHA is 20 ft which limited the folded height to less than 20 ft. because of obstacles and sills on the ships decks and elevators. V-22 design specifications call for operationally spotting a minimum of 30 aircraft on LHA/LHD class ships - considering all factors such as launch spots, elevators, cargo and troop movements, and safety aisles. Figure 7 shows 30 V-22's spotted on an LHA. The V-22 must be able to operate adjacent to the island on a LHA. Requirements for a minimum clearance of 12' 8" from the island to the right rotor tip and 5 foot clearance from the left landing gear to the edge of the deck (Figure 8) coupled with a 1 ft. clearance between the rotor and fuselage in airplane mode results in a maximum wing span of 45.83' and rotor diameter of 38 feet.

Mission requirements include Marine Corps amphibious and land assault with both internal and external payload (Figure 9), Navy combat search and rescue and Air Force special operations missions, as well as a worldwide self deployment (see Figure 10) capability for all services. These missions define the payload/radius, takeoff and landing conditions and speed requirements which in turn drive fuel capacity, power requirements and transmission limits. Cabin internal volume requirements are also specified. Figure 11 shows the guarenteed payload capability for each mission. Requirements are shown and the size of the payload margin indicates those missions that drive the design. The critical missions are the are the Marine land assault - troop lift and the Air Force special operations. The Marine mission is lift limited at takeoff and the Air Force mission is lift limited at the midpoint which restricts takeoff weight. Examination of these missions in detail helped establish transmission limits and maximum internal fuel capacities. The Air Force mission was critical in both aspects. Self deployment dictated the maximum rolling takeoff gross weight and the requirement for maximum internal cabin fuel. One engine inoperative transmission ratings and rates of climb were a consideration. All of the missions require an air particle separator to protect the engines in hostile environments.

The requirement for aft loading of troops and cargo imposes unique aerodynamic and structural constraints on the aft fuselage and limitations on vertical tail depth. Two maneuver requirements - low speed and high speed - also drive the design. The low speed maneuver requires 1.75 g's at 60 kts at sea level standard and determines rotor solidity. A high speed 180° decelerating turn in less than 15 seconds impacts wing loading and wing design to the extent that flaps or other devices are required. The last significant aerodynamic design driver is maximum speed of 275 kts at sea level standard which dictates low drag, high rotor cruise efficiency and is a consideration in both transmission limits and rotor tip speed.

6. Aerodynamic Development

Figure 12 shows the wind tunnel test sequence. The objective of the program was to provide guidance for configuration development, support trade studies and establish an aerodynamic data base to reduce development risk. The test program includes 2-dimensional airfoil tests, a large scale rotor performance and wing download test, unpowered drag and stability tests, powered aerodynamic interaction model tests, aeroelastic stability, spin, engine inlet and nacelle airflow management development tests. To date, there have been 21 tests of 8 models in 8 wind tunnels for 8008 test hours completed. Subsequent sections will describe how test results of key system elements supported configuration decisions. In addition to the testing already completed, wind tunnel tests are planned to first flight in order to posture the Bell-Boeing team to be able to better analyze and interpret flight test results.

6.1 Rotor Development

The V-22 rotor diameter was established to meet shipboard requirements to operate adjacent to the island of an LHA. With the required clearances, the maximum rotor diameter is 38 ft. (see section 5 on design drivers and Figure 8). Aerodynamically, for the same solidity, increasing the number of blades improves both hover and cruise performance because blade/blade interference is reduced. For the V-22, 3 blades were selected based on shipboard compatability constraints which required the wing and blades to be folded for stowage. The XV-15 has demonstrated the viability of 3 blades.

The hub type and hinge offset were selected accounting for control moment requirements, method of control, thrust vector tilt relative to the drive shaft, and hub moments. For tilt rotor applications, differential longitudinal thrust vector tilt acting above the center of gravity is needed for adequate yaw control moments. This is obtained by using a gimbaled hub as compared to a hub type that produces only hub moments. Pitch control uses the same longitudinal thrust vector tilt on each rotor with some hub moments provided by a hub spring. Thrust vector tilt is obtained through the use of conventional longitudinal and lateral cyclic pitch. Rotor system weights are lower for low hinge offset systems compared to rigid, hingeless or bearingless rotor systems. On the basis of these considerations and taking into account the XV-15 hub design experience, a gimbaled rotor providing the equivalent of a 2% hinge offset to increase the hub moment contribution was selected.

Direction of rotor rotation was selected to be the same as the XV-15 with the blades rotating in the direction opposite to the tip vortex in airplane mode (right rotor clockwise when looking forward). This direction improves the span loading and reduces induced drag.

The choice of rotor tip speed and tip speed range (tip speed is reduced in cruise to improve rotor efficiency), was selected based on past experience and taking into account the effects on drive system weight, noise, and performance. Hover tip speed was initially established at 779 ft/sec, the same as the XV-15. This was later increased to 790 ft/sec for the Marines to better match engine output speed characteristics. The Air Force aircraft operates at 820 ft/sec for increased lift.

Trade studies were conducted to determine the optimum cruise tip speeds. Performance, and weight were considerations. Mission fuel was computed for a range of tip speeds. As expected the fuel minimized at a very low tip speed. Weight considerations for rotor frequency placement optimized the payload at a cruise tip speed of 662 ft/sec. The selected tip speed range (662 ft/sec to 820 ft/sec) optimizes mission performance while minimizing weight empty.

Selection of rotor planform, twist, airfoils, and solidity were based on the results of trade studies to optimize hover and cruise performance and obtain maximum lift. Figure 13 compares the airfoils developed for the V-22 rotor with those used on the XV-15. The V-22 airfoils have been optimized relative to the older 64 series sections. Data for the 64 series airfoils were obtained from Reference 2. The XN-28 is 28% thick and used in the root section (r/R = .2). The 18% thick XN-18 is used inboard (r/R = 0.5). The 12% thick XN-12 is used over the main working section (r/R = 0.75) and the 9% thick XN09 is the tip airfoil. Data for these airfoils was obtained by two-dimensional testing in the Boeing Supersonic Wind Tunnel (BSWT). Maximum C_ℓ/C_d in hover, $C_{\ell max}$ at the low speed manuever condition, and C_d at rotor lift coefficients typical of cruise at 250 knots are compared.

Rotors for tilt rotor applications are designed so that the planform favors hover. The selection of blade twist is a compromise between hover and cruise and is usually biased towards hover to obtain maximum lift. Rotor solidity required is large for hover and small for cruise. The thrust weighted solidity resulting from design studies was .1138.

Because of the importance of demonstrating hover capability to reduce program risk, a test was conducted at NASA Ames on the Outdoor Aerodynamic Research Facility (OARF). Cruise performance was not obtained during this testing since it was less critical for the program but will be obtained in large scale prior to flight test. For testing on the OARF, the rotor was scaled to 25 ft diameter and compared with the XV-15 rotor. Figure 14 shows the isolated V-22 rotor on the test stand. Figure 15 shows the improvement of the V-22 isolated rotor over the XV-15 rotor. Testing on the OARF was also accomplished with the other rotor simulated by an image plane and with a wing installed. The complete installed rotor performance (ie, performance with wing in place and image plane) is also shown in Figure 15. Compared to the isolated rotor there is a reduction in thrust for a given power and a reduction in peak figure of merit. This is caused by the wing and image and is attributed to the existence of a region of recirculating flow between the wing and rotor. This pattern was observed during testing using tufts and colored smoke. The downwash that impinges on the wing flows radially outward from the rotor centerline. When it reaches the downwash from the other rotor, both flows are turned upward. Part of this flow is recirculated back through the rotor which causes the loss in performance. The recirculation is large enough to overcome the performance increase of the rotor operating in the partial ground effect of the wing. Reference 3 provides further insight on this phenomenon.

A trade study between low speed maneuver load factor and rotor solidity was conducted after the large scale testing was completed. Payload margin is increased if rotor solidity is reduced because of the weight savings in rotors and controls. On this basis a new thrust weighted rotor solidity of 0.105 was selected and is currently on the V-22. The geometric characteristics of the selected rotor as well as the rotor tested on the OARF are shown in Figure 16.

6.2 Wing Development

Wing span was established on the basis of shipboard compatability, particularly the requirement to operate adjacent to the island of an LHA (See Figure 8). Based on the required clearances, both the maximum rotor diameter and wing span are defined. Maximum wing span is 45.83 ft (defined to the centerline of rotors). Chord selection was the subject of early trade studies in which wing chord was varied while keeping rotor diameter fixed. As the chord increased, aerodynamic drag increased which drove the fuel system capacity. Weight empty decreased at constant wing thickness to chord ratio since the torque box size increased. Other considerations included the impact of wing loading on the high speed maneuver capability. These studies showed that the optimum was flat and a wing chord of 100 inches was selected to maintain the wing chord to rotor diameter relationship similar to the proven XV-15 (C/D of XV-15 = .24, C/D of V-22 = .219).

The V-22 wing airfoil was analytically developed to have good high Mach number penetration while maintaining high lift capability and low drag. The airfoil that was developed is designated the A821201. Wing weight trades showed the lightest wing would have a thickness/chord ratio of approximately 33%. This was clearly unreasonable from aerodynamic considerations of maximum lift, minimum drag, and acceptable drag divergence characteristics. Two wings were tested two-dimensionally in the Boeing Supersonic Wind Tunnel. These were a 23% thick wing similar to the XV-15 thickness and a 25% thick wing. It was decided to retain the 23% thickness/chord wing because of the higher maximum lift and drag divergence Mach number.

Forward wing sweep is driven by the requirement to have 12 inches of clearance between the rotor tip and wing leading edge when the rotor is flapped back 10.5 degrees. In the V-22, the cross shaft is swept forward 6 degrees and is located behind the torque box. This necessitates a midwing gear box to handle the angle changes, accessory drives and an APU. Because the rotors are aligned with the free stream in airplane mode they are splayed out by 6 degrees when rotated to the helicopter mode since they are fixed to the cross shaft at the sweep angle. To maximize hover lift, 3.5 degrees of dihedral are put into the wing which splays the rotors out only 2.5 degrees. To maintain the proper clearances with the flapping blade, the rotor hub centerline is placed 2 ft ahead of the leading edge of the wing at the tip. To provide blade clearance in a straight wing configuration in the cruise mode, the rotor hub would have to be 4 ft ahead of the wing leading edge at the tip. This longer nacelle combined with a higher static torsional moment would increase the empty weight. A midwing gearbox would still be required for accessory and APU drives. On this basis, the six degree forward swept wing configuration was selected. In addition this configuration has been proven in the XV-15.

Flaps are needed on the V-22 to expand the conversion corridor, improve maneuverability at low and high speeds, reduce download (thereby increasing hover gross weight) and provide lateral control. Slotted and plain flaps were tested two dimensionally and on a drag/stability model. The two-dimensional results of $C_{\ell max}$ vs flap deflection are displayed in Figure 17. Slotted flaps were selected for the V-22. The full span flaps are also used as ailerons for roll control, and are therefore called flaperons. They meet the requirements and provide full roll control to beyond wing stall. Figure 18 illustrates the reduction of download due to flap deflection. Download is reduced because of the reduction of vertical drag coefficient on the wing and by the reduction of wing area affected by the rotor downwash. Maximum flap deflection on the V-22 is currently 67 degrees. The optimum angle will be determined during flight test. At the 67° flap angle, during the large scale OARF test, rotor thrust coefficient was varied and the results are shown in Figure 19. Download/thrust reduces as thrust increases. This is attributed to the downwash changes from nearly uniform at low thrust to skewed toward the tip at high thrust. Reference 3 presents a more thorough discussion of this data.

6.3 Fuselage/Sponson Development

The V-22 fuselage evolved from the requirements to carry 24 combat equipped troops. This dictated cabin width, length and height. Overall length was dictated by shipboard spotting. The nose shape was defined by pilot vision requirements and the need for avionics space, provisions for a gun and stowage of the nose landing gear. The requirement for a rear loading ramp, however, had a significant impact on the afterbody design. Increasing requirements for sponson volume to house fuel and equipment also had a large impact on the design. The afterbody and sponson developments significantly affected the overall aerodynamic characteristics while changes to the nose had little impact.

Figure 20 shows the candidate afterbodies that evolved during initial design studies. The initial baseline had a more complex loading ramp design than the "C-130 type" afterbody. Both have the same nose, forward fuselage and overall length. The "C-130 type" afterbody displayed better stability and lower drag characteristics and was selected for continued development.

Three sponson arrangements evolved (Figure 21). These are an initial baseline which resembled a cambered wing mounted on the back of the fuselage, an inverted cambered wing to decamber the overall configuration and a long increased volume sponson similar to those on the CH-47 helicopter. Althought the decambered sponson showed the lowest overall drag, the CH-47 type sponson was selected since it had a larger internal volume for fuel and equipment. There was no stability change for any of those tested and the current design has been optimized from this point.

6.4 Empennage Development

Several empennage configurations were considered for the V-22. Candidate geometries were selected based on being shipboard compatible without folding and with a ground clearance during flare greater than 15 degrees. Clearance during loading and unloading of outsized cargo was also a consideration. The candidate tails (Figure 22) include an "H" tail configuration similar to the XV-15 and a "T" tail arrangement sized with a single vertical fin limited in height for shipboard compatibility with two outboard finlets to provide additional directional stability. A conventional tail was not considered because it would require folding both the horizontal and vertical tails for the same stability levels since it is not end plated.

Aerodynamic selection criteria included static longitudinal and directional stability, linearity of the aerodynamic characteristics and longitudinal control power. Other considerations included the structural aspects - frequency placement and weight, survivability and vulnerability, and reliability and maintainability. A trade study was conducted to understand these issues.

Both tails could provide the required stability but weight trades showed the "H" tail lighter than the "T" tail configuration because of the penalties of attaching the horizontal to the top of the vertical. In addition, the "T" tail exhibited undesirable directional characteristics through zero sideslip. On the basis of this trade study and the XV-15 experience the "H" tail was selected for the

V-22. Single and double hinge elevators were studied. A single hinge elevator was selected since it met the requirement to trim the airplane at maximum thrust with flaps down and is less complex than the double hinge design.

6.5 Engine Inlet Development

Mission requirements dictate the need for an efficient engine inlet and a particle separator to permit worldwide operations over any terrain and a wide variety of environmental conditions. Other considerations include efficient operation at high angles of attack representative of transition. In addition, such practical nacelle design considerations as the underslung engines driving forward and up to the main rotor transmissions which block the inlets and the rotor spinner protruding forward of the inlet impose unique requirements in designing an efficient inlet. The requirements established for the design include:

- low inlet losses in hover and cruise
- 95% sand and dust separation
- meet engine distortion limits throughout the flight envelope

A comprehensive program of analysis, design and wind tunnel testing was undertaken to meet these stringent requirements.

The engine inlet lip radii and the internal features of the air flow and scavenge ducts were designed using the potential flow panel code VSAERO developed by Analytical Methods, Inc. Trajectory analyses using spherical particles and simple bounce assumptions indicate near 100% separation efficiency.

A 40% scale model of the nacelle was built with a powered "stub" rotor to provide simulation of the rotor downwash, and ejectors to obtain the correct inlet and exhaust mass flows. A portion of wing was added to better simulate real external flows as influenced by the wing circulation. This model was tested in the low speed, high angle of attack range in the Boeing Vertol V/STOL Wind Tunnel and at high speed and low angles in the Boeing Transonic Wind Tunnel. Results are shown in Figure 23. Measured inlet pressure recovery in hover and cruise were good; .9965 in hover and .9955 at .5 Mach number. Maximum circumferential distortion index as a function of engine mass flow is also shown. This parameter is a measure of the flow distortion at the engine face. The test data indicates a low level of distortion, below 3%, which will ensure smooth engine performance. References 4 and 5 further describe this work.

6.6 Test/Theory Correlation

In addition to developing the aerodynamic configuration and establishing a firm foundation for the design, an important aspect of the test program was to validate the analysis tools so that the wind tunnel data base could be extended to conditions other than those tested. Having validated the analysis tools, they can now be confidently used in the design process. Test/theory validation is shown for rotor performance, aerodynamic loads and aerodynamic characteristics - all important in the V-22 design. Figure 24a shows the comparison between the isolated rotor performance measurements made in the OARF in terms of Figure of Merit vs. Thrust Coefficient and lifting line and lifting surface theory. Both methods use the prescribed wake formulations of Kocurek

(Ref. 6). Lifting line theory underestimates the performance at the peak while the lifting surface method predicts the peak well but overestimates performance at lower thrust coefficients. Nevertheless, both methods produce reasonable correlation. Figure 24b shows the good test-theory correlation of rotor cruise efficiency obtained through full scale testing of the XV-15 rotors in the Ames 40 x 80 ft wind tunnel.

Two potential flow panel codes have been validated against V-22 wind tunnel test data and reported in Reference 7. The first, designated A502 (Pan-Air), is a high order panel method formulation developed by the Boeing Company. The second code is VSAERO, a low order panel method developed by AMI, Inc. Only the correlation with VSAERO is shown because the Pan-Air results are similar. Figure 25 compares measured upper and lower surface pressure distributions at the centerline of the complex V-22 fuselage with predictions for two angles of attack; 5° and 20°. As can be noted, the correlation is excellent over both surfaces to behind the wing and is only slightly degraded aft of this point. This indicates the flow is generally potential and well behaved over much of the V-22 fuselage. The upper surface peaks corresponding to the wing maximum suction are very well predicted.

Correlation of the aerodynamic characteristics with model test data for the complete V-22 configuration is shown in Figure 26, from Reference 7. Figure 26a compares computed and measured lift coefficient with angle of attack. Pitching moment characteristics are compared in Figure 26b in two ways. The first uses the program without modifications, and the second corrects pitching moment for the difference between the measured and predicted pressures shown in Figure 25. This is an indication of the sensitivity of the pitching moment to variations in the pressure distribution. Figure 26c compares measured vs computed induced drag coefficients. VSAERO does an adequate job in predicting trends at moderate lift coefficients, but as viscous effects become dominant, the analysis diverges from the experimental data.

The test/theory correlation discussed in this section validates the rotor performance, aerodynamic characteristics and loads methodologies. It provides a solid foundation to extend the test data base and use the analytical methods confidently in the design.

6.7 Aerodynamic Characteristics

On the basis of the aerodynamic configuration testing, and data base development and analysis discussed in preceeding sections, the salient aerodynamic characteristics of the full scale V-22 are presented. Figure 27 shows the rotor aerodynamic characteristics for both hover and cruise. Typical operating conditions are noted in the figures. In Figure 28, trimmed lift and drag coefficients for the complete aircraft are shown. The aircraft data are regular and linear with typical operating conditions shown. Longitudinal stability characteristics are portrayed in Figure 29 in terms of neutral point vs. Mach number. Data is shown at the USMC weight (M^2C_L = .089) for both power on and power off.

The reduction of neutral point due to power effects, are typical of all propeller driven aircraft with tractor propellers. Adequate stability at the most aft CG is available throughout the speed range. The forward CG is established by the criteria to trim maximum thrust with flaps down and considerations of available trim while carrying external loads in the V/STOL mode.

There was some initial concern about the spin characteristics of the V-22. Consequently, a test of a 1/20 scale powered spin model (the first ever tested) was conducted on the rotary balance in the NASA Langley 20 foot spin tunnel. Testing was conducted by Bihrle Applied Research, Inc. Figure 30 shows the model in the tunnel. The V-22 configuration with rotors off and on, provides a significant amount of retarding forces against the spin. The rotors produce exceptionally large amounts of damping at all angles of attack. The test data and the post test spin analysis predict no spins even for the most pro spin control settings.

An assessment of the V-22's aerodynamic cleanliness is shown in Figure 31. It is the usual portrayal of equivalent parasite drag versus wetted area for lines of equivalent skin friction coefficient. The V-22 lies within the utility, propeller driven airplane class, and as expected, considerably above jet transports.

A comparison of the V-22's overall hover and cruise efficiency is presented in Figure 32. Aircraft hover efficiency (Figure 32a) is defined as the ideal power required to hover at a given weight divided by the actual total power, including all losses. This is similar to the concept of Figure of Merit for an isolated rotor. The V-22 data is estimated and the data for the other helicopters have been obtained from service flight manuals. The V-22 is more efficient than the other helicopters because it has a higher isolated rotor Figure of Merit due to its high twist (θ_T = -10 to -18° for the helicopters, -47° for V-22), modern airfoils and advanced planform, with approximately the same losses. The V-22 also has a higher aircraft cruise efficiency (defined as velocity times weight divided by the total power) than the helicopters as shown in Figure 32b, but is lower than a conventional turboprop aircraft such as the C-130.

7. V-22 Performance

A summary V-22 performance characteristics is presented in Figure 33 and compared to the CH-46E and the CH-53D which are current inventory aircraft performing the assault mission. V-22 performance is based on guarenteed levels while the CH-46E and the CH-53D were obtained from published NATOPS flight manuals. Hover ceiling, payload radius capability in performing the land assault Marine mission and flight envelope comparisons are presented. Figure 33a compares hover ceiling for standard day. Payload for the land assault Marine mission is shown in Figure 33b with the requirement noted. Figure 33c shows the standard day flight envelope comparison with the speed requirement noted. The V-22 is over 125 kts faster than the CH-46E and CH-53D and offers a quantum jump in flexibility and capability.

8. Conclusions

- The V-22 aerodynamic development program is substantially completed and illustrates how an aggressive test program very early in the development cycle reduces program risk and helps provide a highly efficient aircraft, fully responsive to the missions.

- Validated methods are available to support both the current design and any follow on efforts in tilt rotor development.

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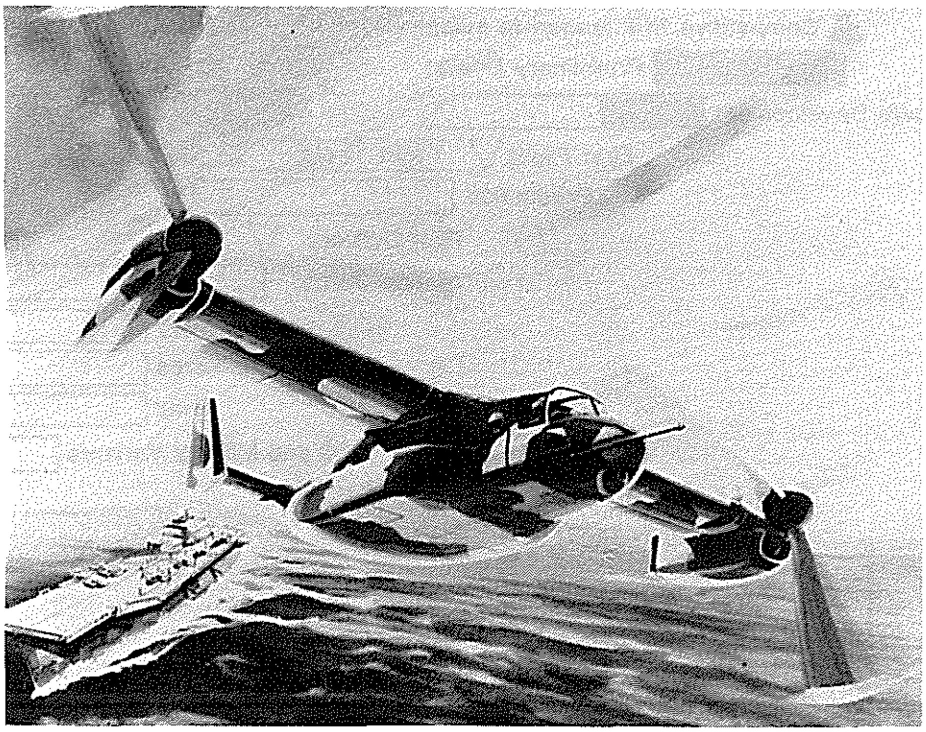


Figure 1. MV-22 Osprey

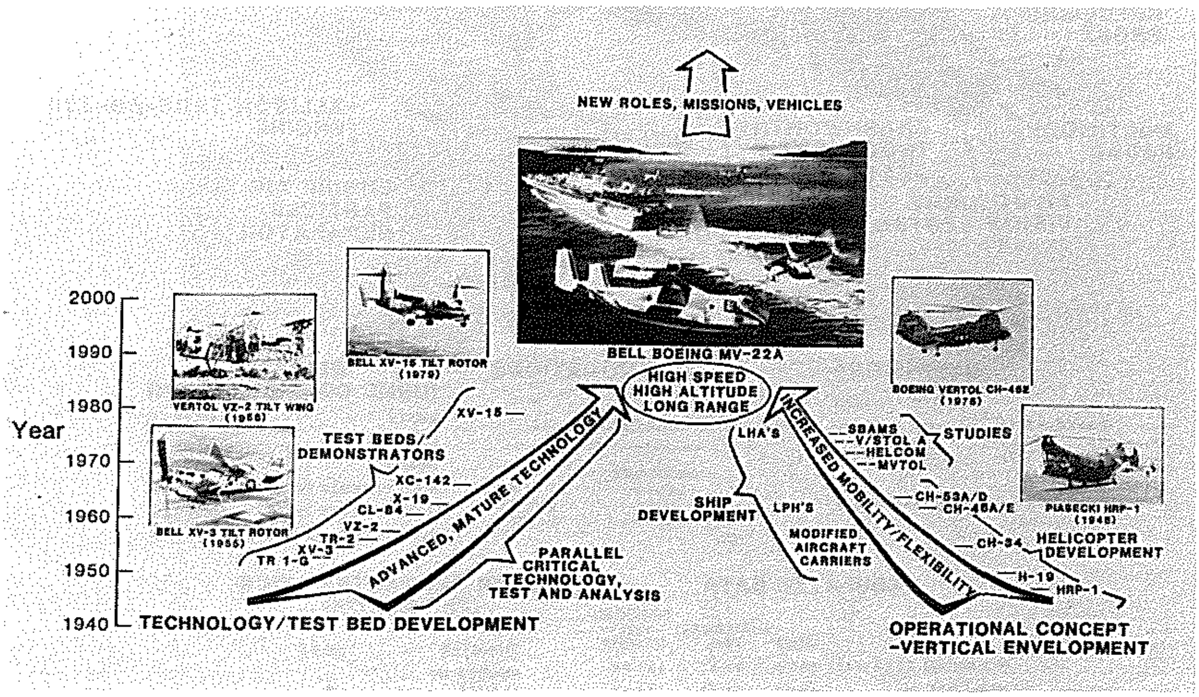


Figure 2. Program Evolution

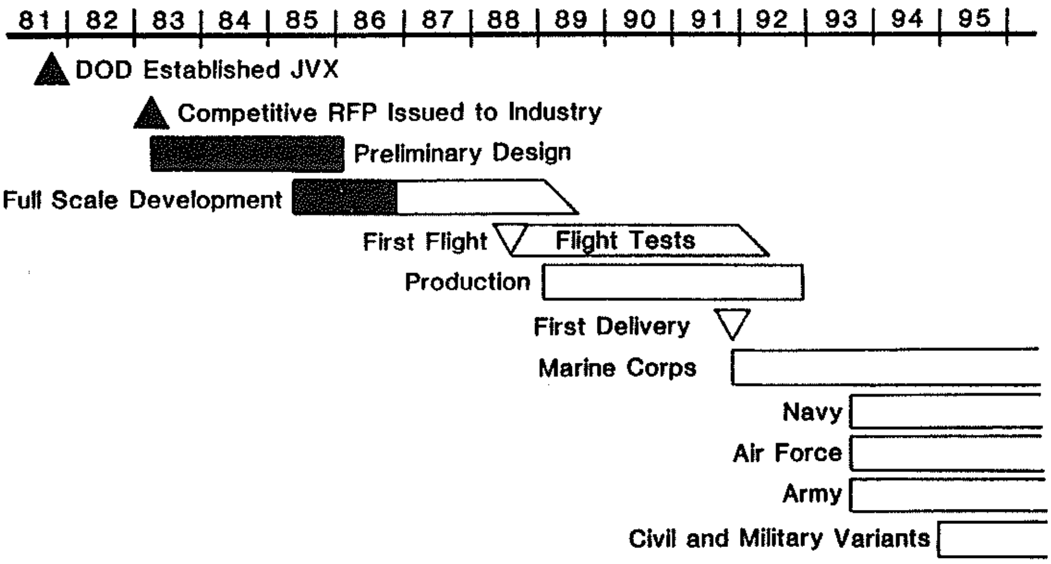
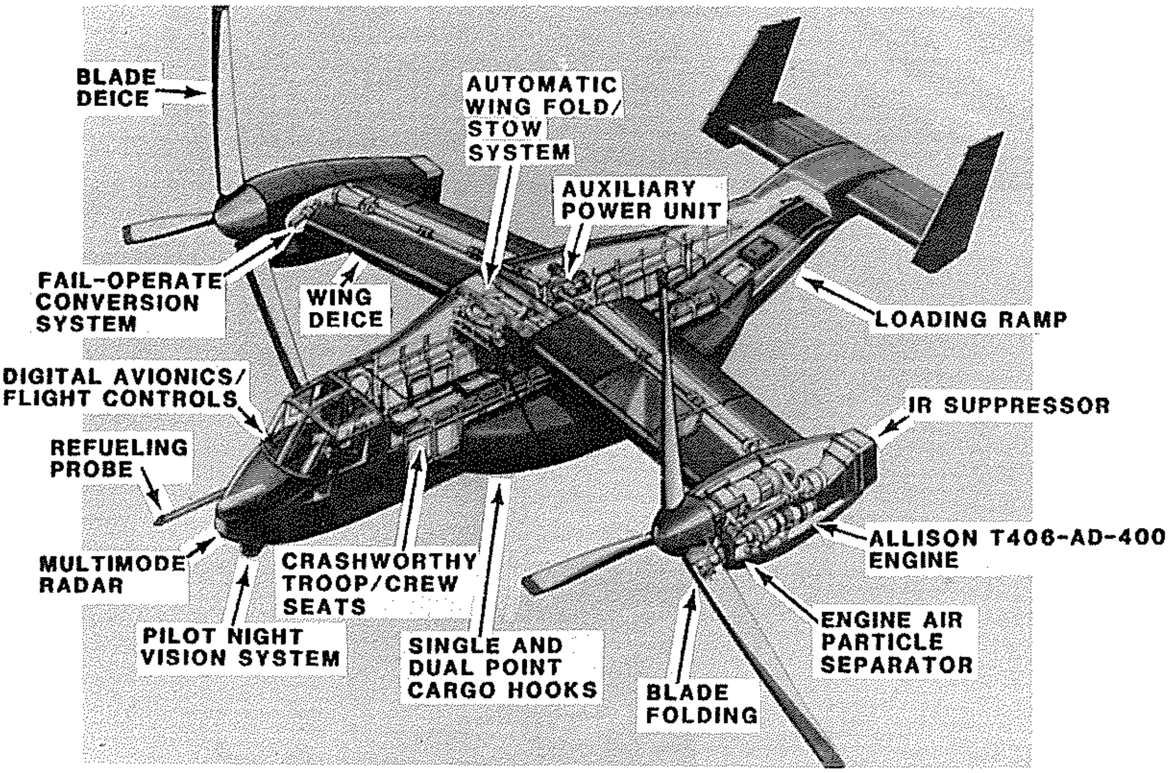


Figure 3. Overall Program Schedule



DIMENSIONS

	LENGTH	HEIGHT	WIDTH
MAXIMUM (FT)[1]	57.33	21.76	84.58
FOLDED (FT)	62.58	18.10	18.42

[1] HELICOPTER MODE

ACCOMODATIONS

CREW	3
TROOP SEATS	24
LITTERS	12
CABIN SIZE	
- LENGTH	24.17 FT
- WIDTH	5.92 FT
- HEIGHT	6.0 FT

WEIGHTS (USMC CONFIGURATION)

EMPTY	31,818 LB
DESIGN	39,500 LB
COMBAT	42,712 LB
MAX. TAKEOFF (VTO)	47,500 LB
MAX. TAKEOFF (STO)	55,000 LB
SELF DEPLOYMENT (STO)	60,500 LB

TABULATED DATA

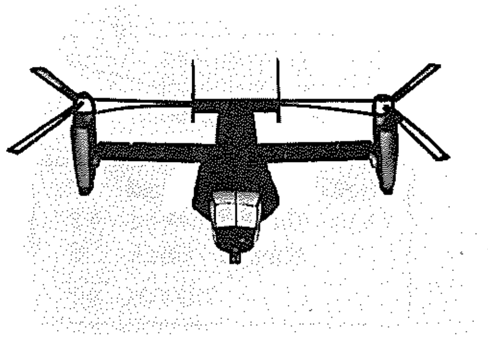
	WING	HORIZONTAL TAIL	VERTICAL TAIL (TOTAL)
PLANFORM AREA (FT^2)	382.0	87.41	131.84
SPAN (FT)	45.83	17.73	11.17
ASPECT RATIO	5.5	2.36	1.69
CHORD (FT)	8.33	7.5	6.63
SWEEP ANGLE (DEG)	-6.0	0.0	--
DIHEDRAL ANGLE (DEG)	3.5	0.0	--
INCIDENCE ANGLE (DEG)	0.0	-3.0	0.0

ROTOR CHARACTERISTICS (PER ROTOR)

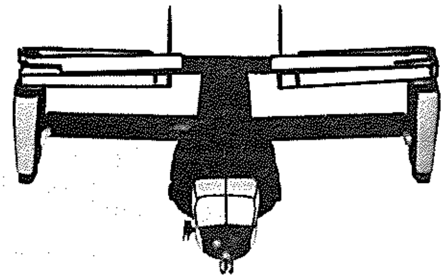
DIAMETER	38 FT
NUMBER OF BLADES	3
BLADE CHORD	
- ROOT	34.3 IN
- TIP	22.0 IN
THRUST-WEIGHTED SOLIDITY	0.105
RPM	
- MINIMUM	316
- NORMAL	333 TO 397
- MAXIMUM	417

Figure 4. V-22 Design Characteristics

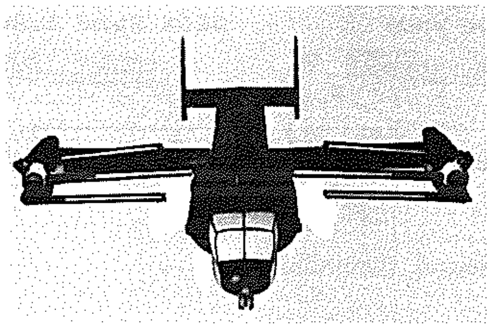
(a) Aircraft lands in helicopter mode



(b) Two outboard blades of each rotor are folded inboard



(c) Nacelles rotated to cruise mode



(d) Wing rotated 90° clockwise within 90 seconds

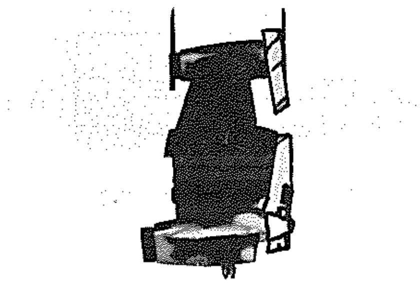
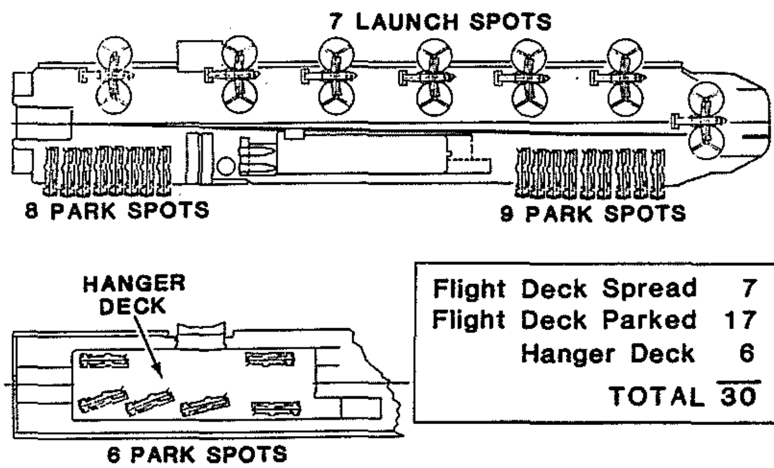


Figure 5. Wing Stow Sequence

- **LHA Shipboard Compatability**
  - 7 Launch spots
  - 23 Parking spots (on and below decks)
  - Conduct takeoff/landing operations adjacent to island
- **Missions**
  - Marine assault
  - Navy CSAR
  - Air Force special operations
  - Self deployment
- **Aft Loading of Troops/Cargo**
- **Maneuver Requirements**
  - Low speed: 1.75 g's at 60 knots at sea level/standard
  - High speed: Level, decelerating turn (180°) in ≤15 seconds at 3000 FT/91.5°F
- **Speed Requirement**
  - V_{max} ≥275 knots at sea level/standard

Figure 6. Configuration Drivers



Flight Deck Spread	7
Flight Deck Parked	17
Hanger Deck	6
TOTAL	30

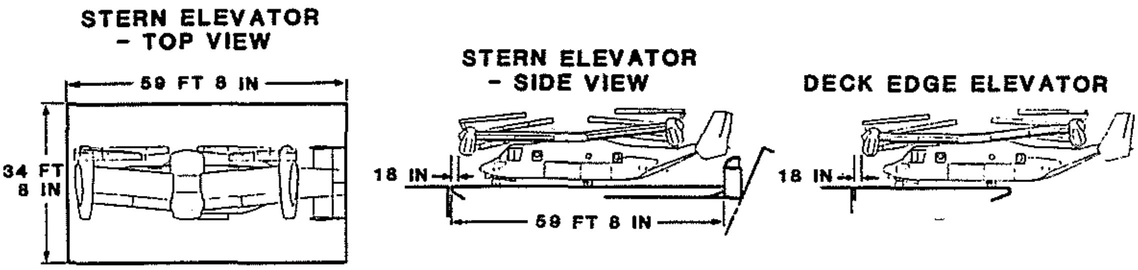


Figure 7. LHA Shipboard Compatability

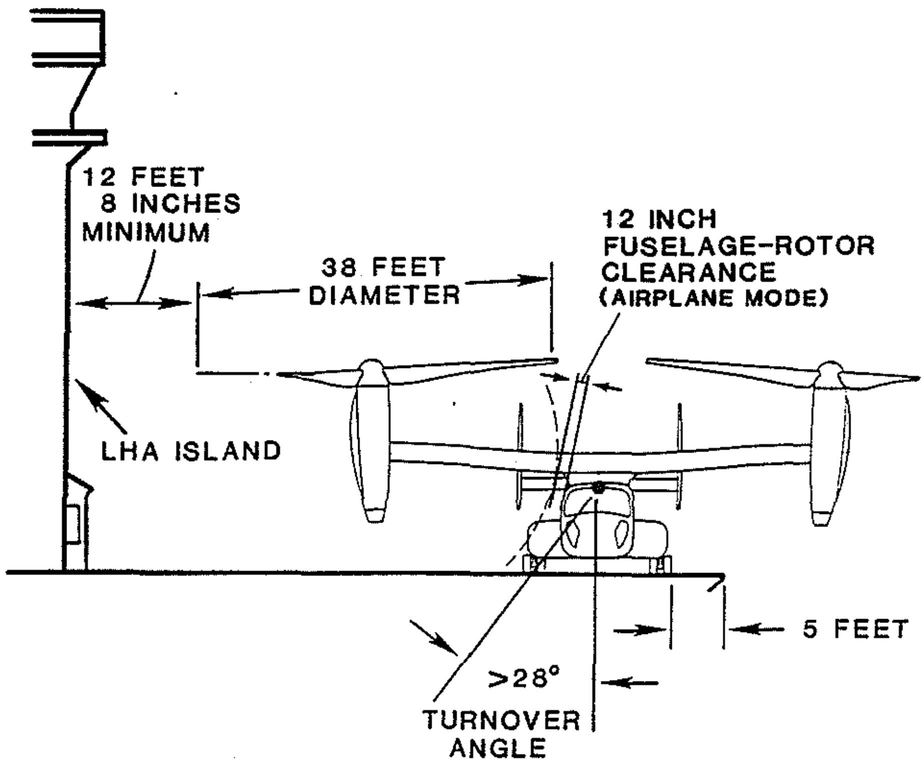
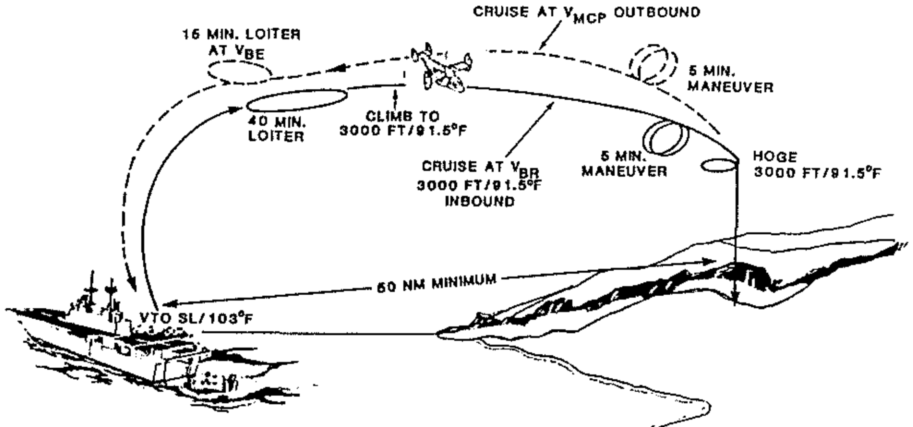


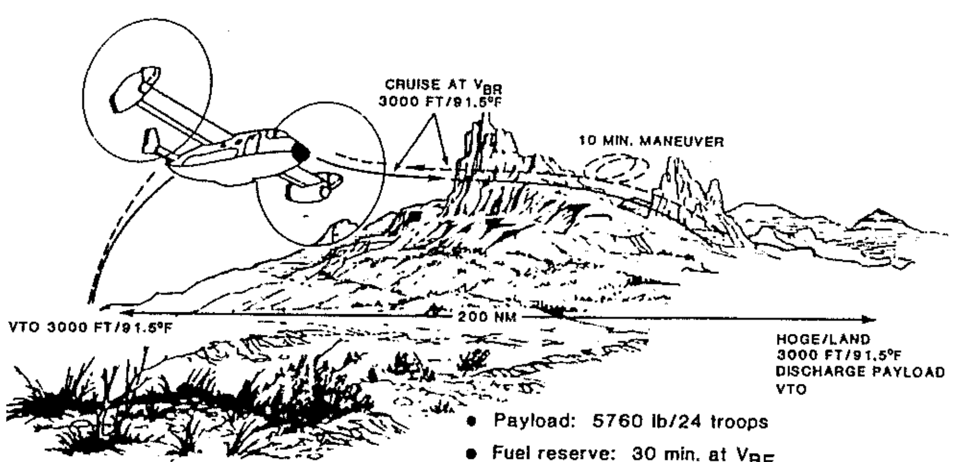
Figure 8. Rot‑r/Wing Shipboard Constraints

Amphibious Assault - Troop Lift
(MARINE CORPS)



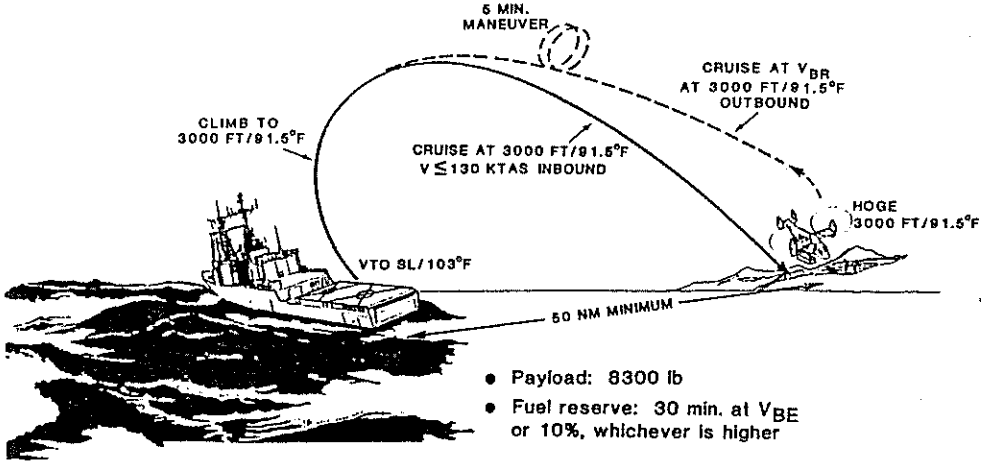
- Payload: 5760 lb/24 troops
- Repeat mission without loiters or maneuvers
- Fuel reserve: 30 min. at V_{BE} or 10%, whichever is higher

Land Assault - Troop Lift
(MARINE CORPS)



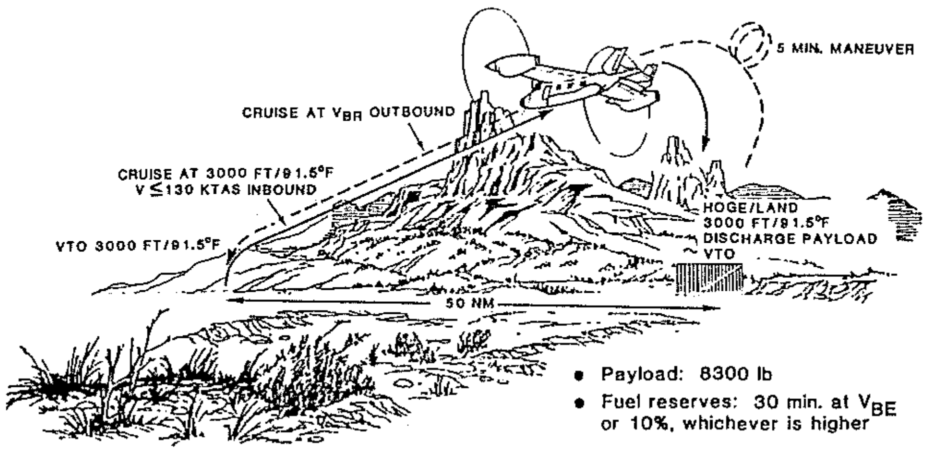
- Payload: 5760 lb/24 troops
- Fuel reserve: 30 min. at V_{BE} or 10%, whichever is higher

Amphibious Assault - External Cargo Lift
(MARINE CORPS)



- Payload: 8300 lb
- Fuel reserve: 30 min. at V_{BE} or 10%, whichever is higher

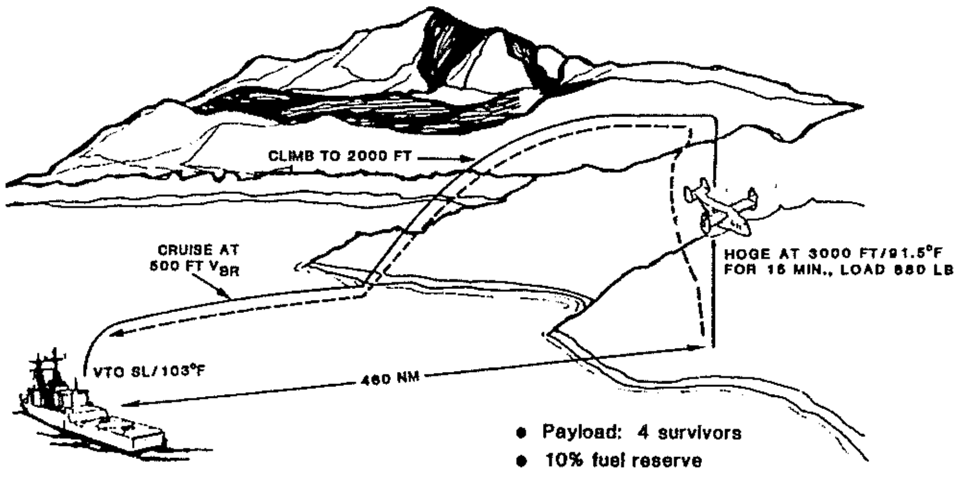
Land Assault - External Cargo Lift
(MARINE CORPS)



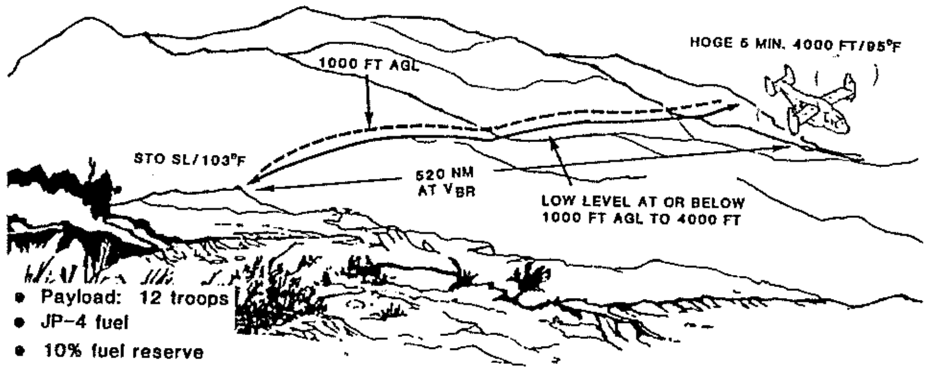
- Payload: 8300 lb
- Fuel reserves: 30 min. at V_{BE} or 10%, whichever is higher

Figure 9. Marine Corps Missions

Combat Search and Rescue
(NAVY)



Long Range Special Operations
(AIR FORCE)



Self Deployment Intra/Inter-Theater
(ALL SERVICES)

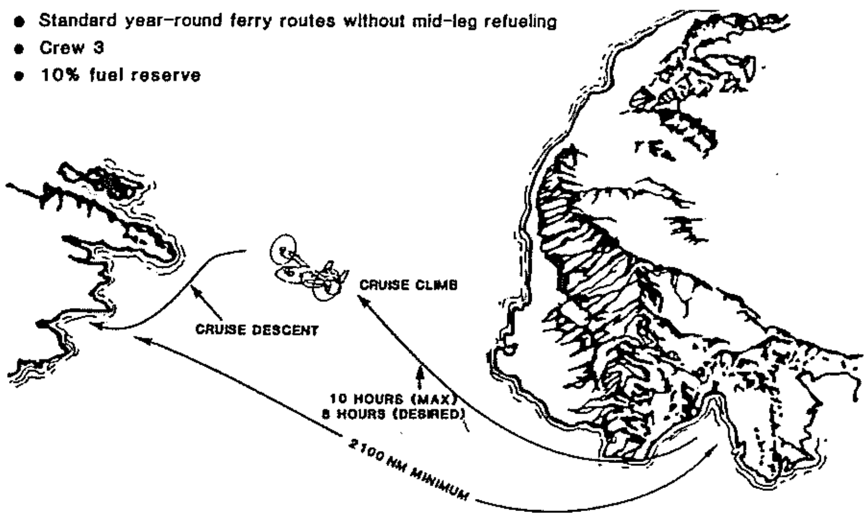


Figure 10. USN, USAF, and Self Deployment Missions

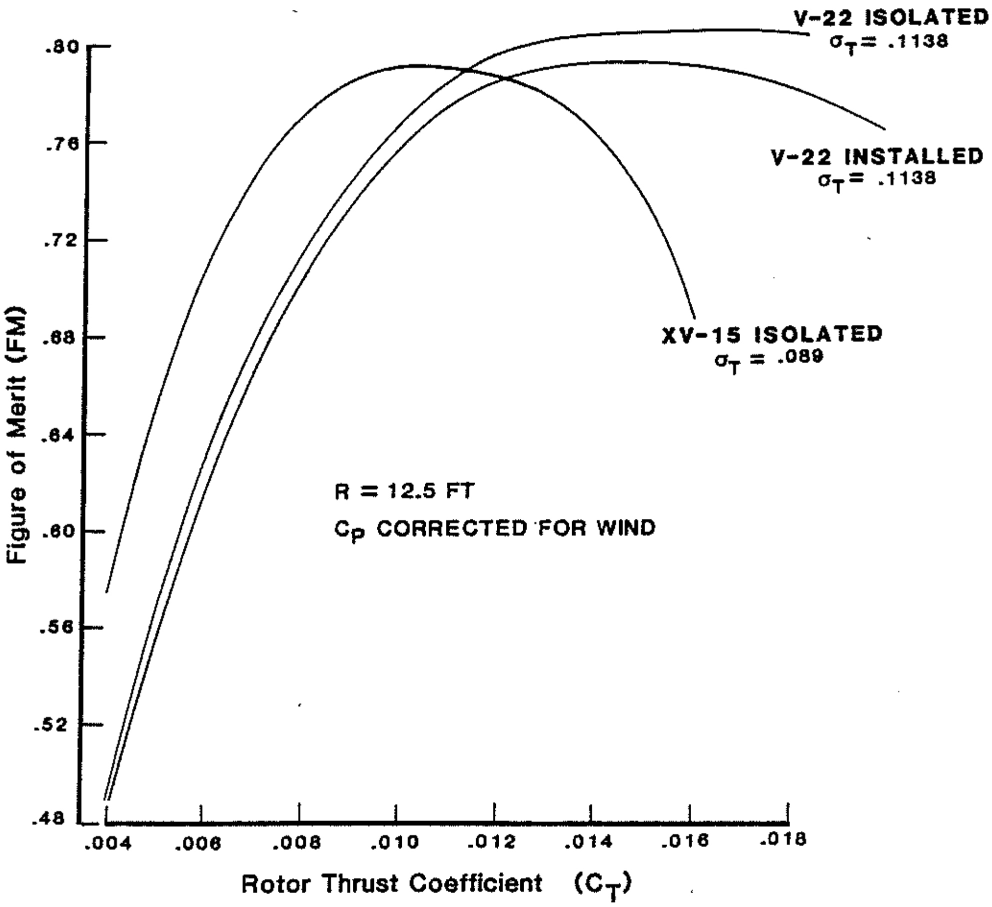


Figure 15. Hover Performance Comparison, V-22 and XV-15

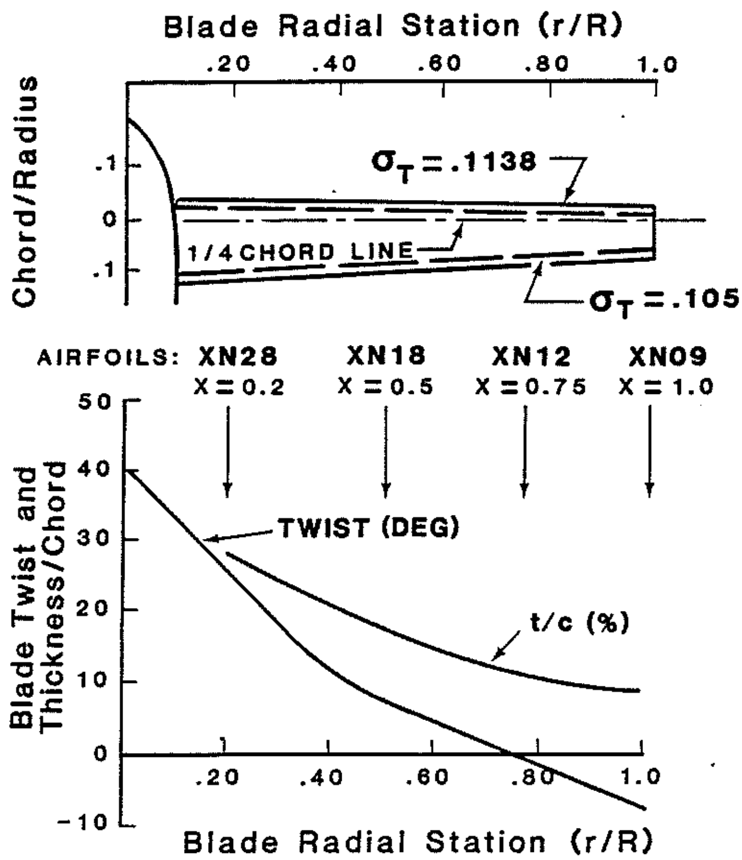


Figure 16. Rotor Geometric Characteristics

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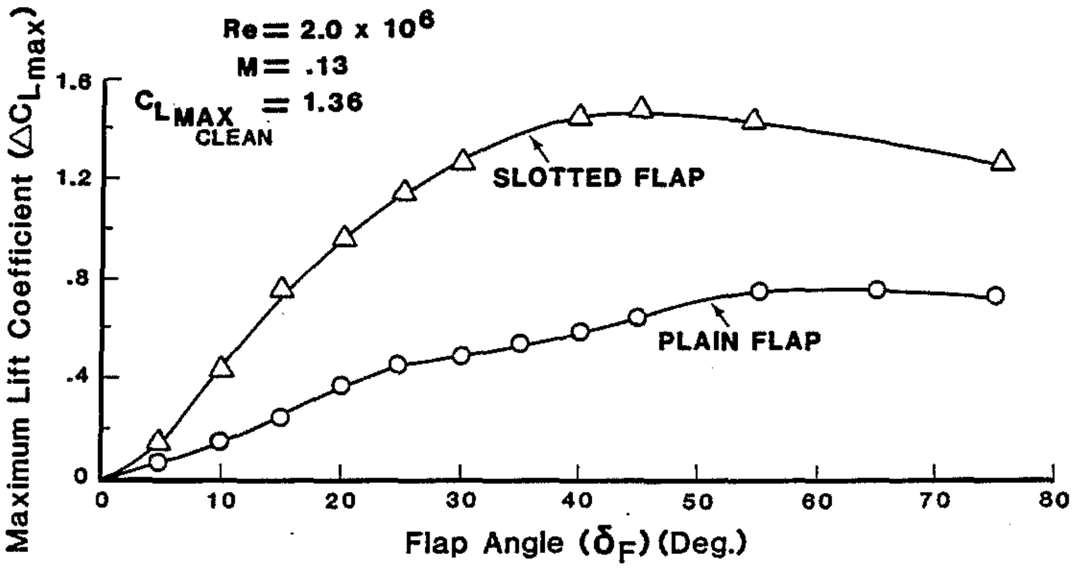

Figure 17. Slotted Flap Advantages

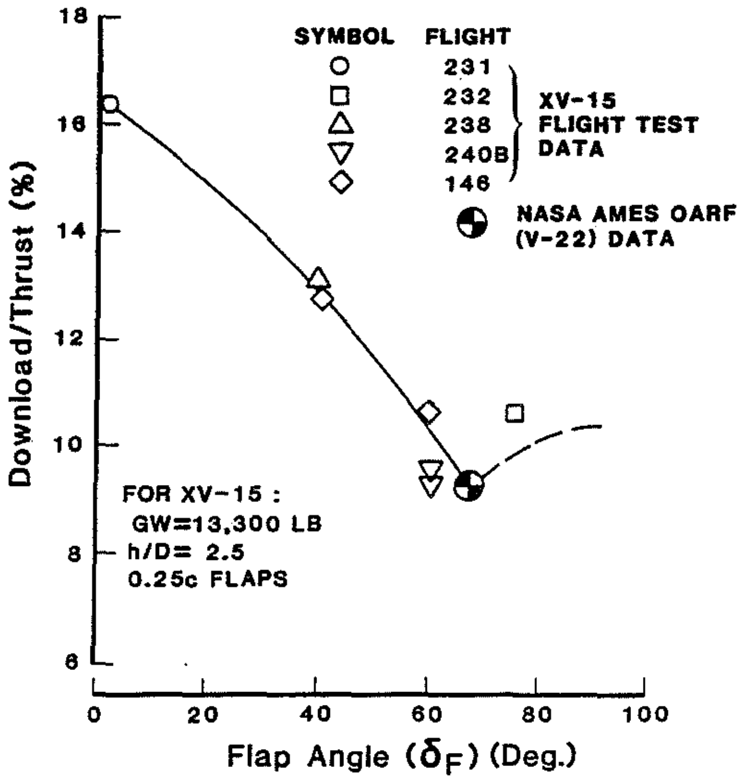

Figure 18. Effect of Flap Angle on Download/Thrust

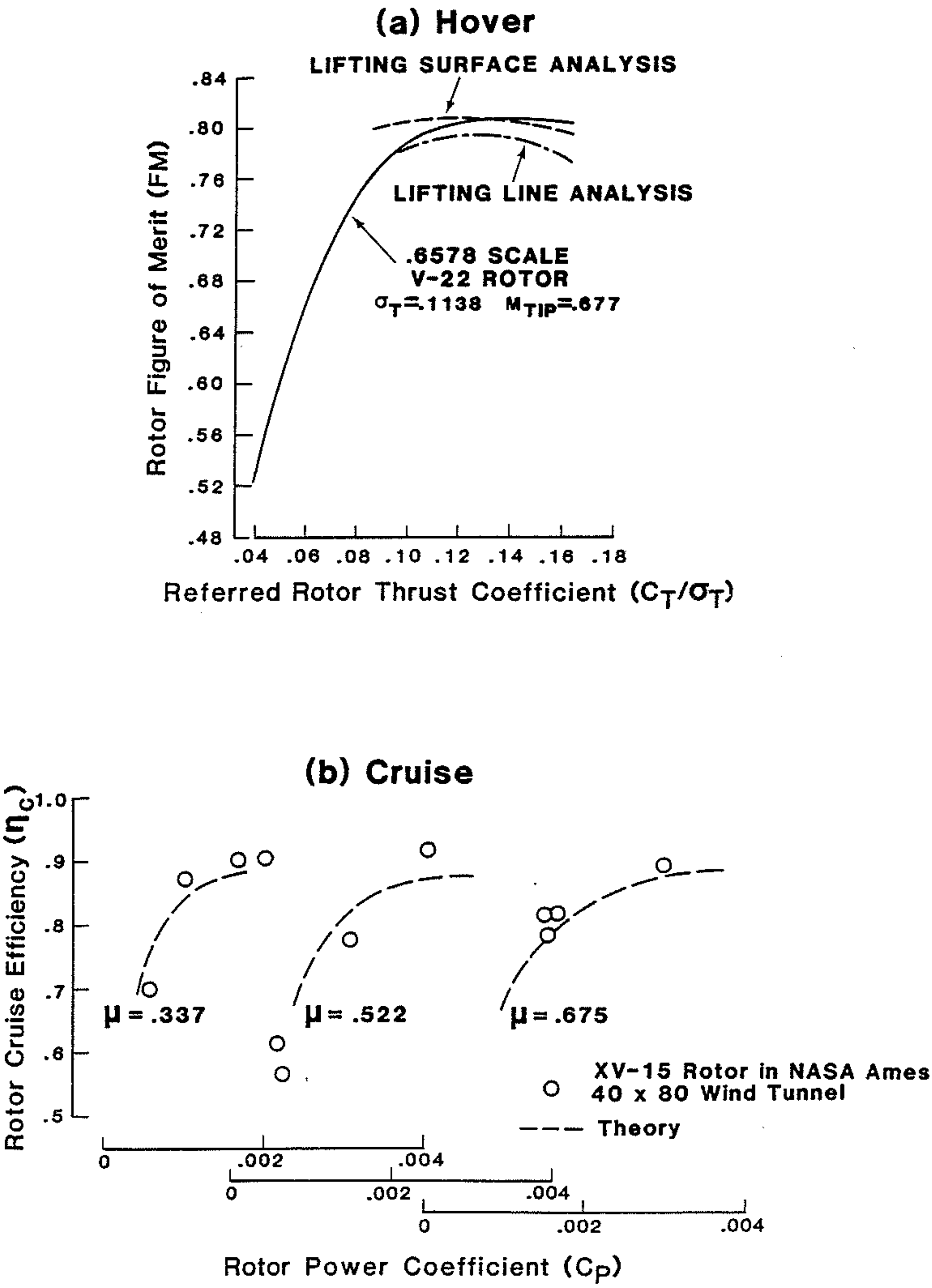

Figure 24. Rotor Performance - Test/Theory Comparison

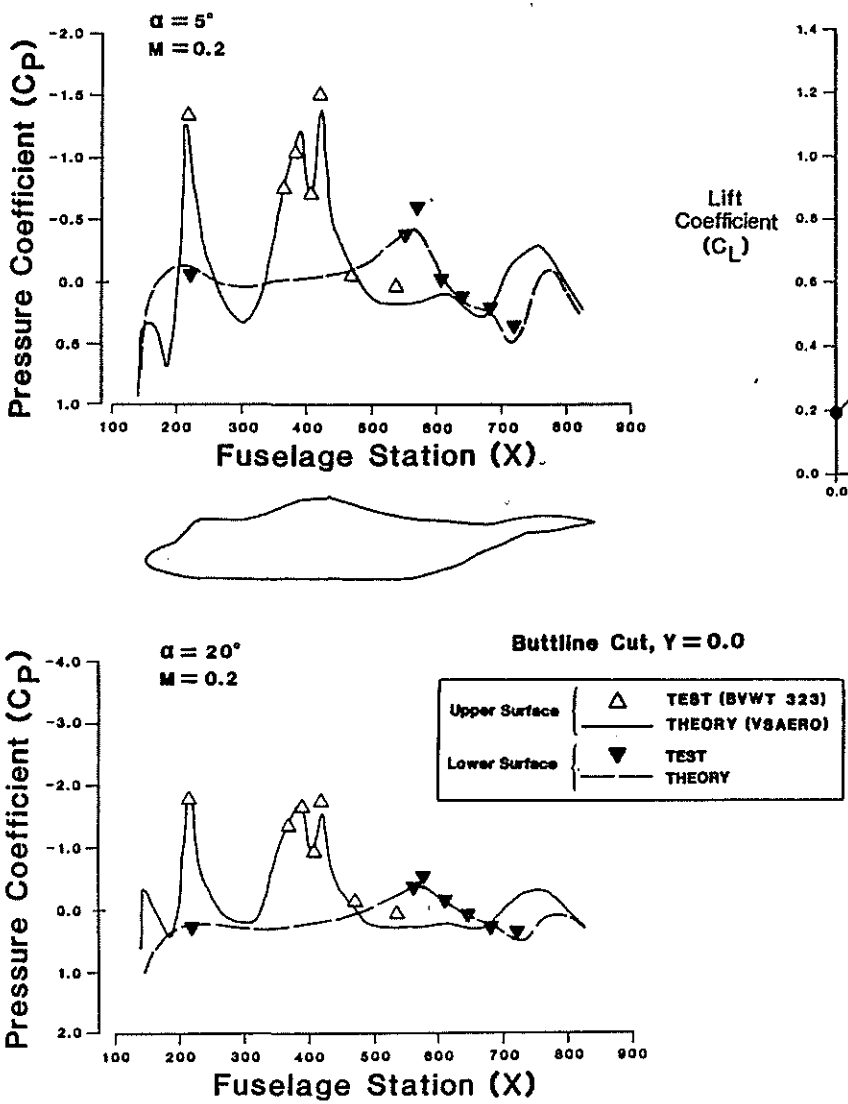

Figure 25. Fuselage Pressure Distribution Correlation

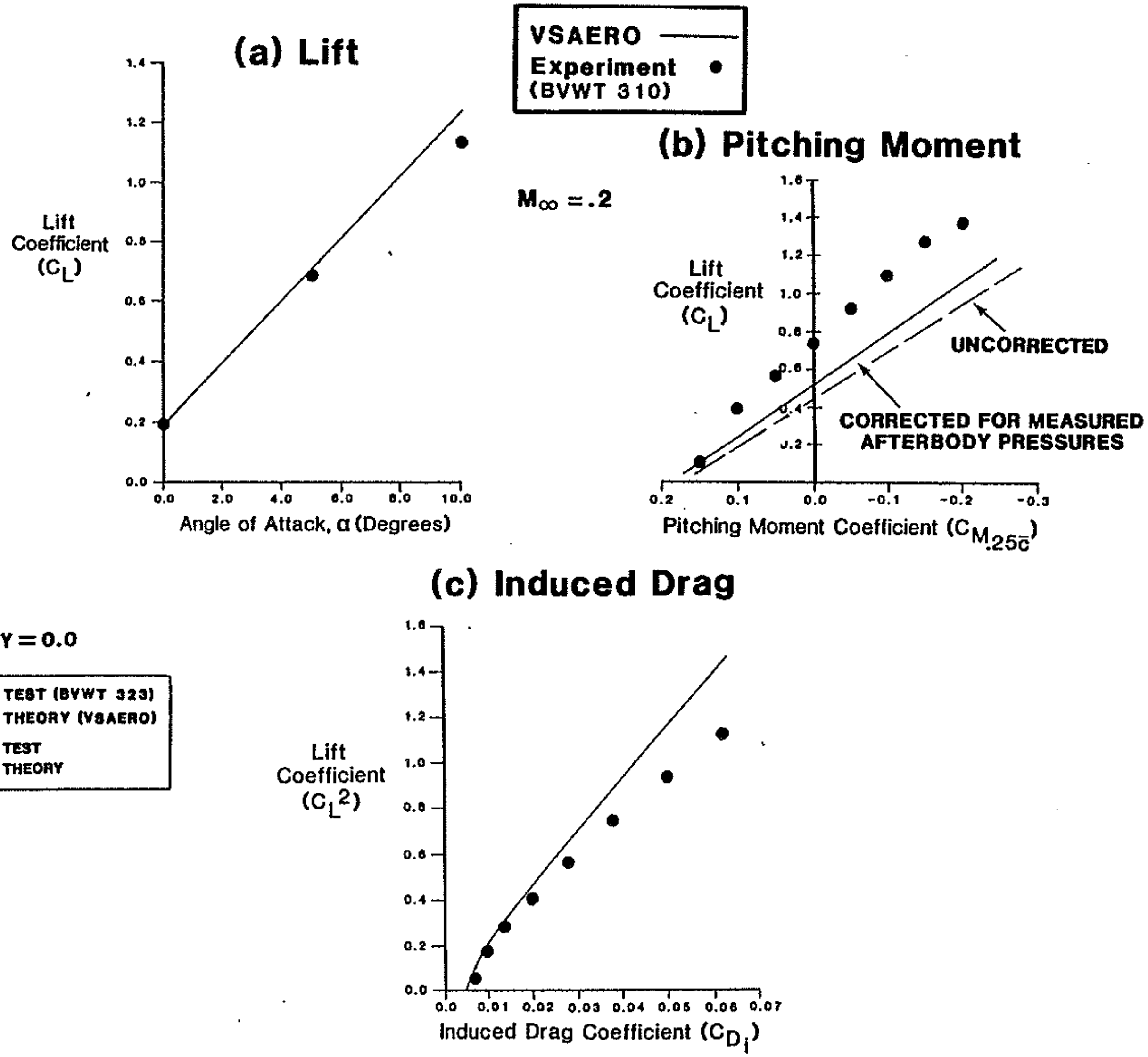

Figure 26. Aerodynamic Characteristic Correlation

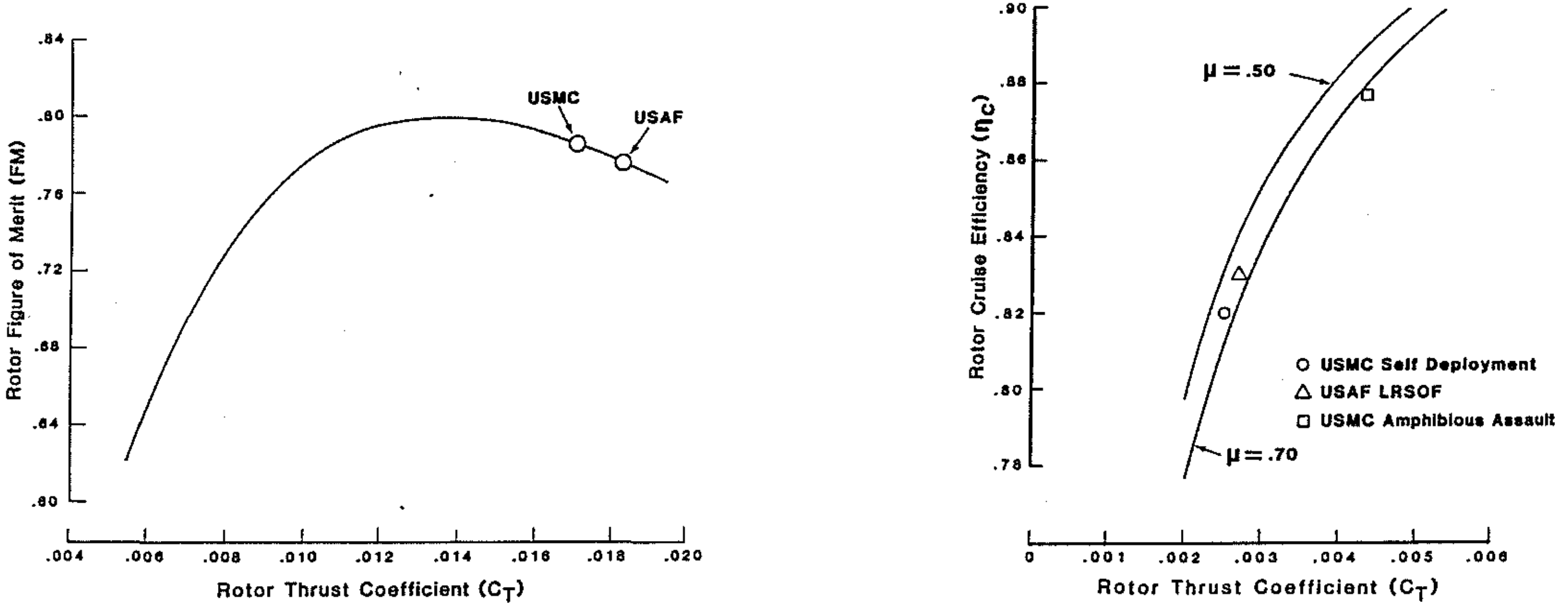

Figure 27. Full Scale Rotor Characteristics

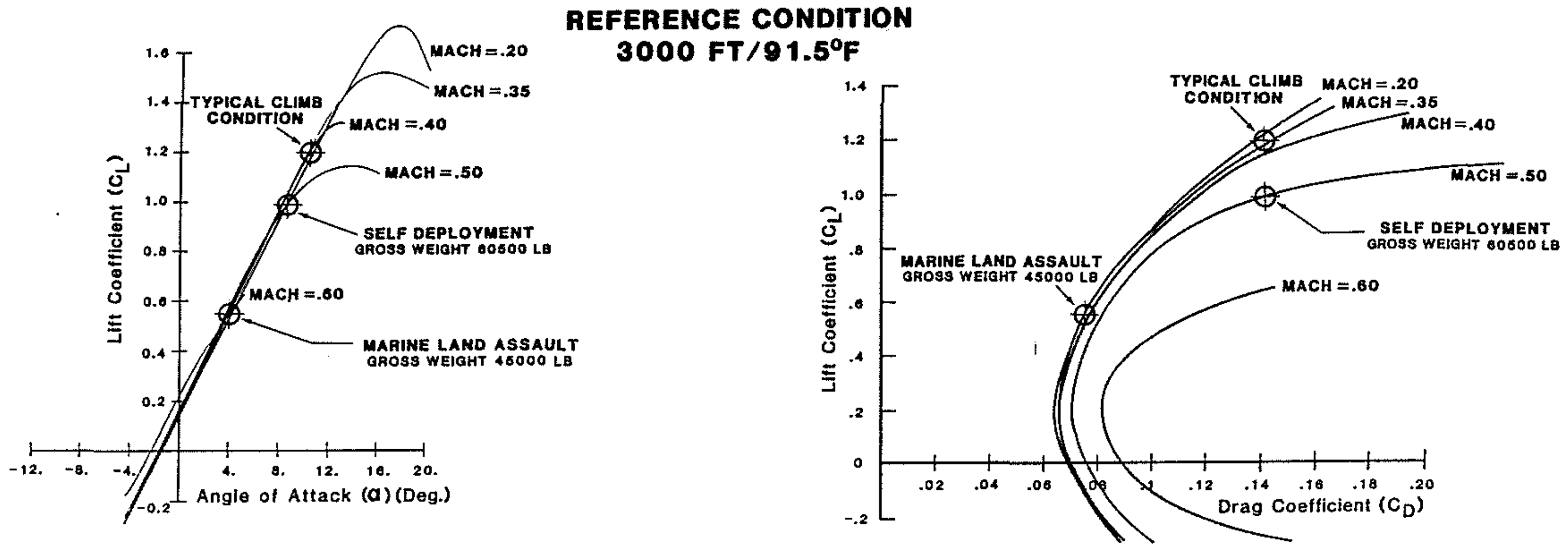

Figure 28. Full Scale Airframe Characteristics (Cruise)

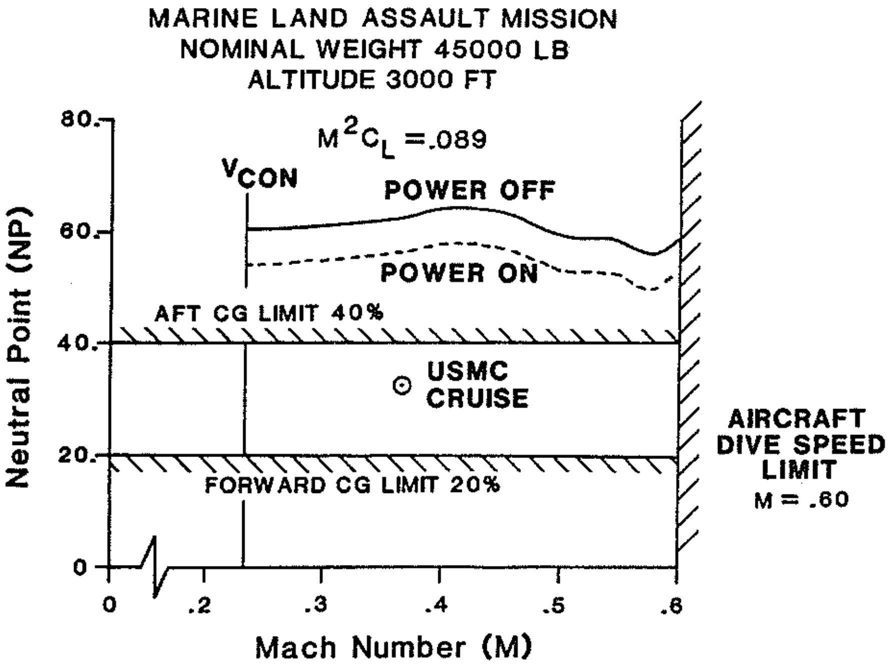

Figure 29. USMC MV-22 Stability Margin

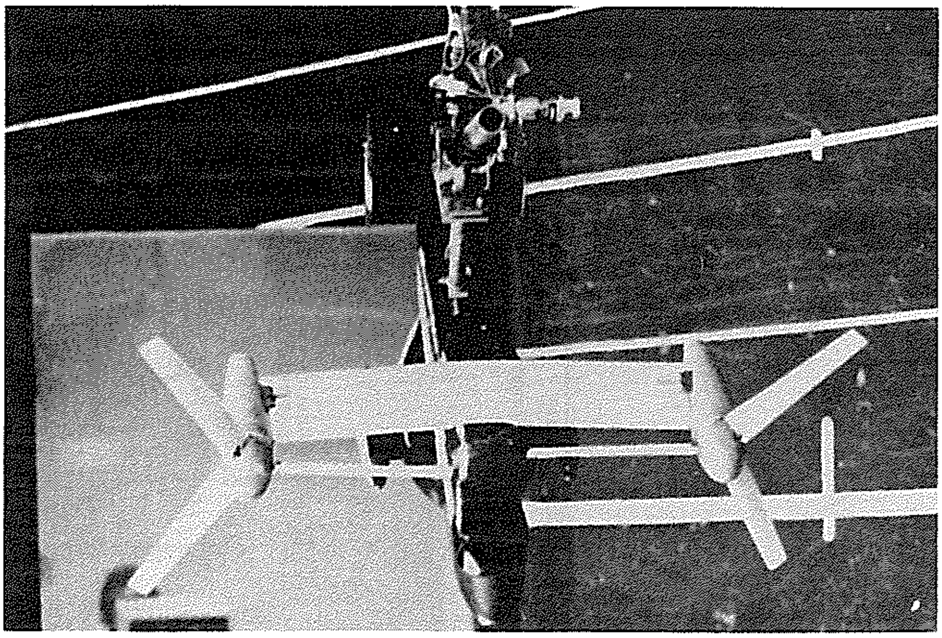

Figure 30. V-22 Spin Model in Langley Spin Tunnel

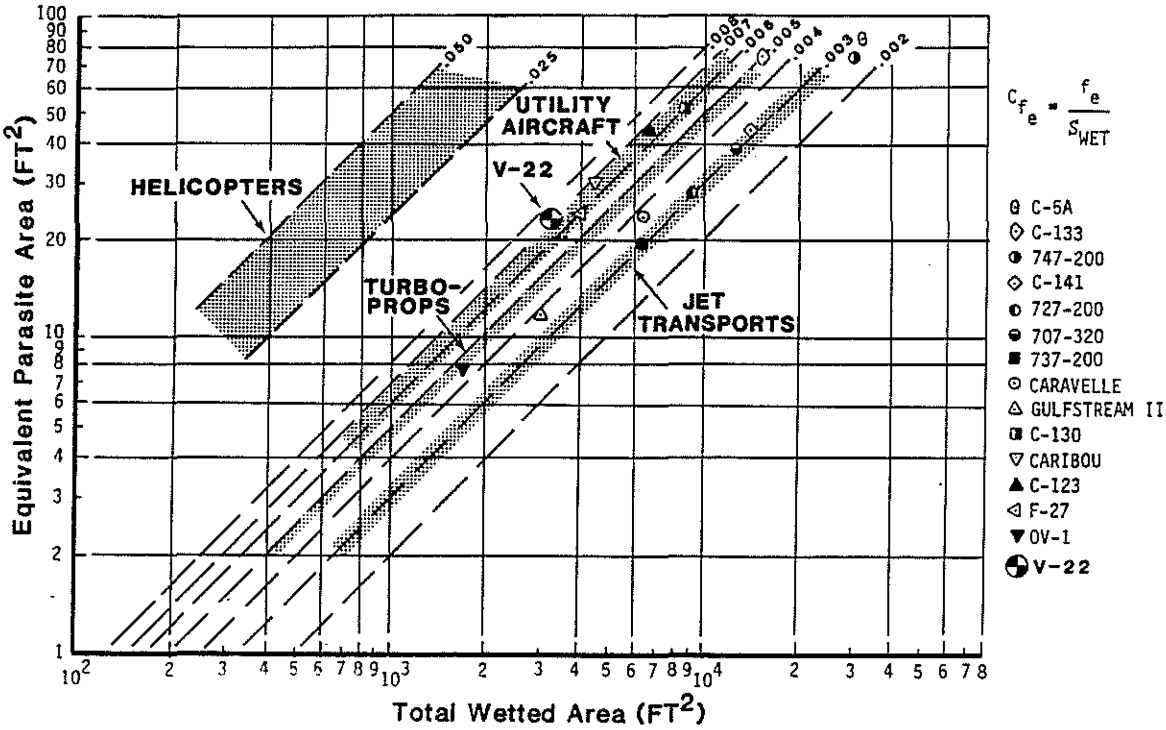

Figure 31. Aerodynamic Cleanliness Comparison

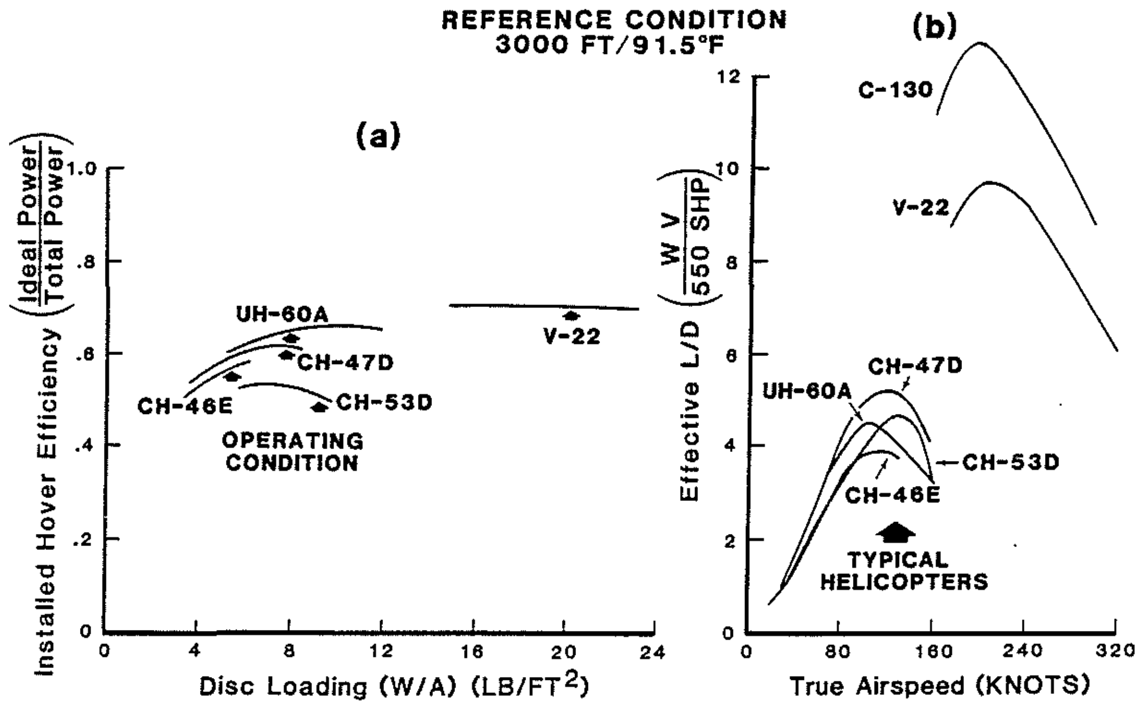

Figure 32. Aircraft Efficiency Comparison

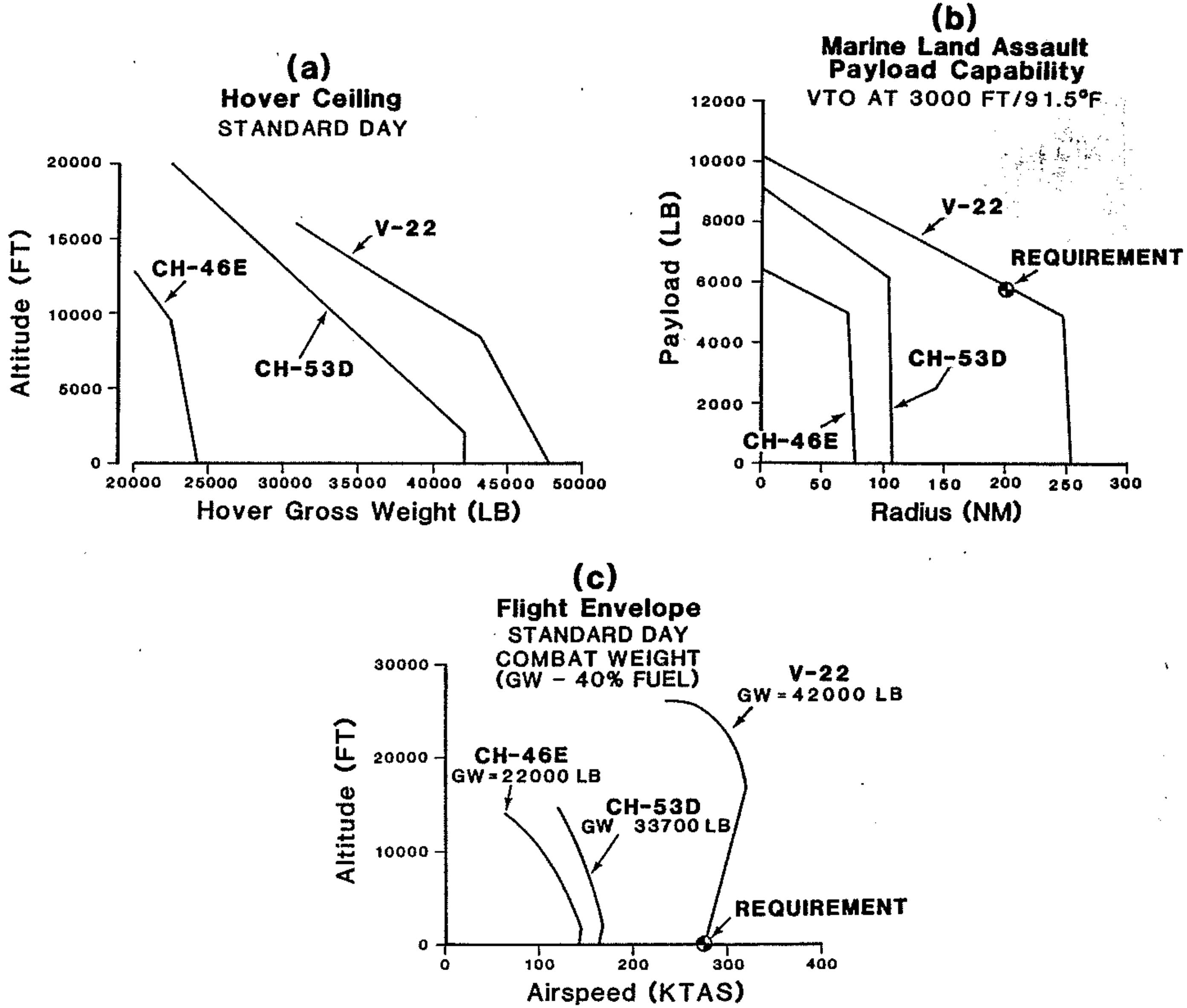

Figure 33. V-22 Mission Performance Comparison