Multimission STOVL Application of a Hybrid Powered-Lift System

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Short Takeoff and Vertical Landing (STOVL) aircraft are options for future replacement of sea-based Conventional Takeoff and Landing (CTOL) aircraft. A conceptual design study was conducted to evaluate the feasibility of a minimum-cost modification of the Lockheed S-3A airframe to an S-3 STOVL configuration. The STOVL concept is based on the use of four TF34 turbofan engines and the application of Lockheed's Advanced Internally Blown Jet Flap/Vectored Thrust (AIBF/VT) hybrid powered-lift system. The S-3 STOVL deck performance estimates are presented along with mission performance comparisons with four CTOL aircraft. These CTOL aircraft are the C-2A, E-2C, S-3A, and KA-6D for the Carrier On-board Delivery, Airborne Early Warning, Antisubmarine Warfare, and tanker missions respectively.

Introduction

IN Sept. 1977, Admiral J.L. Holloway, the then Chief of Naval Operations (CNO), published his paper[1] on transitioning naval air to an all-Vertical or Short Takeoff and Landing (V/STOL) air force, if and when this feasibility could be successfully demonstrated. It was based on the need for expanding and dispersing sea-based aviation assets to reduce vulnerability and increase operational flexibility for countering the adversary threat. Two categories of V/STOL aircraft of interest were identified; of these, the subsonic, multimission aircraft was targeted for development first to reduce the number of aircraft of this type within the fleet. In 1978, however, the Navy decided to defer commitment to major V/STOL hardware development due to affordability and unresolved technical problems. Meanwhile, it commissioned a Sea-Based Air Master Study.[2]

The Sea-Based Air Master Study compared a number of potential aircraft alternatives for postulated U.S. Navy missions. These include 1) Conventional Takeoff and Landing (CTOL)—catapult launch and arrested recovery; 2) Short Takeoff and Landing (STOL)—unassisted takeoff (400-ft deck roll) and arrested or unarrested recovery; 3) Short Takeoff and Vertical Landing (STOVL)—unassisted short takeoff and vertical landing; and 4) Vertical or Short Takeoff and Landing (V/STOL)—vertical or short takeoff and landing. V/STOL and STOVL aircraft are superior to CTOL aircraft operating at sea due to the following inherent factors: greater operational flexibility, shorter deck cycle, higher sortie rate, ability to maintain a continuously ready deck, independence from wind over deck, more efficient utilization of deck space, continued use of damaged flight deck, unconstrained use of available aircraft, and unarrested safe landing with hung ordnance.

The purpose of this study is to develop a conceptual medium-speed, multimission STOVL configuration that requires a minimum aircraft development time span and cost. The logical approach is to modify an existing airframe and engine. This paper discusses the design feasibility and presents the results of preliminary performance estimates for the conceptual STOVL aircraft based on postulated design requirements. Mission performance evaluation results for this aircraft are compared with the performance of existing CTOL aircraft for four missions.

Design Considerations

To develop an aircraft for each naval support-type air mission is prohibitive due to defense budgetary constraints. Analyses of mission requirements reveal similarities among different missions. It should be possible to size a general STOVL aircraft for all support missions. The present study is based on the Navy's stated requirements for medium-speed, multimission aircraft and low-cost objectives.

The sizing of naval support aircraft can be done conveniently by converting payload, time-on-station, hover, mission radius, and other fuel-consuming aircraft maneuvers into an "equivalent range."[3] Table 1 summarizes these mission parameters for support-type aircraft. It appears that an aircraft having a 10,000 lb payload, a cruise speed of 350 knots, and an equivalent range of 3,500 n.mi. could satisfy all of these missions. These conditions result in an aircraft with a maximum takeoff gross weight of 40,000–50,000 lb.

Two important factors in sea-based aircraft design are the vehicle's physical dimensions and weight. Considerations relevant to these factors include the spotting factor, elevator and hanger deck limiting dimensions (i.e., length, width, and vertical height), and elevator weight limitations. Furthermore, the unassisted deck run for the STOVL aircraft must be limited to 400 ft, corresponding to the length of the catapult run for a typical carrier manned in the alert posture. In-flight refueling capability is also a desirable factor for increasing the versatility of the design. Arresting gear backup capability for engine-out conditions must likewise be considered.

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Table 1 Naval support A/C mission parameters

Mission	Payload 1000 lb	Mission radius n.mi.	On station time, h	Cruise speed, knots	Equivalent range, n.mi.
ASW					
Submarine search	5–6	150	3–4	>250	2780
Contact investigation	0	400	1.5	>350	2660
AEW					
Defensive mission	10	50-230	3–4	>150	3220
Offensive mission	10	400	0.5	350	2440
Marine assault (MA)	5–10	500	0.1	>250	2350
Carrier On-board Delivery (COD)	7.5	1200 (2200)		>250	3500
Tanker	5–10	100	1	350	2030
Combat, search and rescue (CSAR)	1–2.5	500	0.5	350	1950
Long-range rescue	2.5	1200	1	350	3500
Surface attack (SA)	5	400	0.5	350	1710
General utility	10			350	3500

Design Constraints

Due to the cost and time required to design and develop an entirely new aircraft, the modification of an existing airframe and the use of existing engines, or derivatives thereof, are the logical approaches to this conceptual design study. In addition, a powered-lift system compatible with this design approach is used.

Considering these STOVL design requirements, the Navy/Lockheed S-3A aircraft has been selected as the appropriate airframe because of its size, gross weight, existing in-flight refueling capability, and relatively modern design. The S-3A is a high-wing, twin-turbofan-powered, carrier-based, basically antisubmarine warfare (ASW) aircraft. To achieve a minimum-cost modification of the S-3A, the design constraints are the retention of the S-3A fuselage, vertical and horizontal tails, landing gear, and wing spar box structure; the retention of the wing and vertical-tail folds; engines mounted inboard of the wing folds; and no ducting across the fuselage. The structural design changes are confined to the engine installation/nacelles and the leading- and trailing-edge flap systems.

Powered-Lift System

A concept that is a hybrid of the Lockheed Advanced Internally Blown Jet Flap (AIBF) and the Vectored Thrust (VT) concepts is selected to provide powered-lift to the S-3 STOVL for its adaptability. This Lockheed multimode STOL/STOVL/VSTOL system is characterized by excellent lift and control augmentation, high effectiveness, and built-in thrust vectoring.

The basic AIBF concept is a wing trailing-edge flap system originally developed for STOL application. Figure 1 shows that the AIBF consists of a main flap and lower-surface flap elements hinged along longitudinally displaced lines that move apart during flap deflection to create a variable-cavity, plenum-flap duct. The availability of a large duct permits the use of low-pressure airflow for blowing. This makes the AIBF compatible with aircraft powered by high-bypass ratio turbofan engines. Simultaneous blowing is provided from a small slot at the knee of the main flap and a fixed-gap slot further downstream, for boundary-layer control (BLC) and from a lower slot near the trailing edge in the manner of a pure jet flap. A short-chord, low-inertia, fast-acting control flap located near the jet-flap exit has a deflection range of −30 (trailing edge up) to +90 (trailing edge down) deg relative to the main flap. The control flap is used to vector the jet-flap thrust to increase or decrease lift in the powered-lift mode and as an aileron in the conventional flight mode.

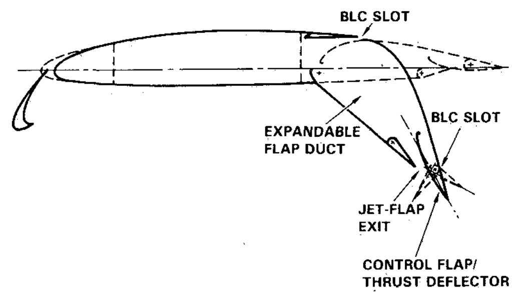

Fig. 1 AIBF basic concept.

The advantages of the AIBF system over conventional internally blown flaps are noteworthy. The AIBF system uses low-pressure, cool fan air, instead of hot high-pressure compressor bleed air, for blowing. This eliminates structural weight due to insulation and thick-walled air ducts. Its variable-cavity flap duct feature provides the necessary duct area for handling large quantities of low-pressure blowing air with minimum duct losses and without requiring a large and heavy fixed duct. The built-in thrust vectoring capability of the control flap allows symmetric, asymmetric, or differential deflections for direct lift, drag, and roll control. Additional descriptions of the AIBF are found in Refs. 4 and 5.

For STOVL application, the AIBF is combined with a forward vectored thrust nozzle. In this arrangement, the control flap of the AIBF system acts in conjunction with the forward nozzle.

Propulsion System

For support-type aircraft, high-bypass ratio engines are desirable for cruise and loiter efficiency considerations. Table 2 lists four existing engines in the thrust range of interest for the S-3 STOVL application. Since the S-3A has only approximately 96 in. of vertical clearance from the ground to the undersurface of the wing, large-diameter engines (CFM56-3 and PW2037) pose serious foreign object and hot gas ingestion problems. Also, a two-engine design would require transfuselage cross-ducting or cross-shafting to ensure engine-out safety.

The TF34 and the FJR710 provide greater vertical ground clearance. In their four-engine configurations they do not require transfuselage cross-ducting, as the pair of engines on each side are cross-ducted. However, the constraint of

Table 2 **High-bypass ratio engine technology (sea level, standard day)**

	TF34-GE-400	FJR-710/600	CFM56-3	PW2037
Max. thrust, lb	9275 (37,080)$^{a}_{4}$	14,330 (57,320)$^{a}_{4}$	20,000 (40,000)$^{a}_{2}$	37,600 (75,200)$^{a}_{2}$
SFC, lb/h/lb	0.363	0.34	0.37	0.32
Bypass ratio (BPR)	6.23	6.5	5.03	5.8
Fan pressure ratio (FPR)	1.47	1.48	1.60	1.7
Comp. ratio at max, rpm	20	22	22.6	26.9
Max. envelope diam, in.	52.0	57.1	64.0	84.8
Length, in.	100.0	92.5	93.0	141.4
Dry weight, lb	1478 (5912)$^{a}_{4}$	2160 (8640)$^{a}_{4}$	4278 (8556)$^{a}_{2}$	6675 (13,350)$^{a}_{2}$

[a] 4 and 2 engine values are in parenthesis.

mounting the engines inboard of the wing fold (a maximum of 120 in. for mounting two engines with their nacelles on each side of the fuselage) makes the FJR710 engine installation unacceptable. On the other hand, two TF34s per side require 104 in. allowing 16 in. for nacelle and separation. For this reason, the TF34 engine is selected to power the S-3 STOVL. To avoid excessive interference drag, one nacelle pod houses both engines on each side. Figure 2 shows the external differences between the S-3A and the conceptual S-3 STOVL configurations.

The AIBF system for the S-3 STOVL extends to 70% of the span of the wing. It has inner- and outer-wing flap segments divided at the wing fold line as shown in Fig. 2. The plenum-flap duct is common to both flap segments. To prevent leading-edge flow separation under extremely high lift coefficient conditions in the STO mode, the leading-edge slat of the S-3A is replaced by an advanced flap system.

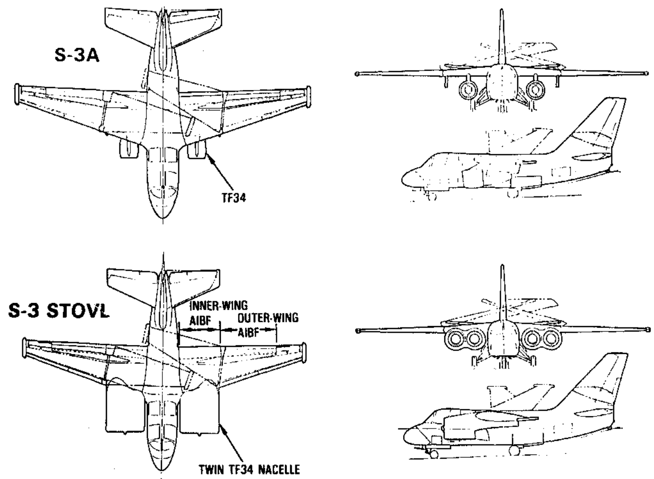

Fig. 2 **CTOL and STOVL configuration comparison.**

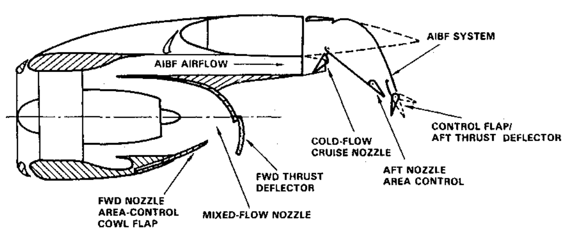

Fig. 3 **Integrated propulsion/powered-lift system concept for S-3 STOVL.**

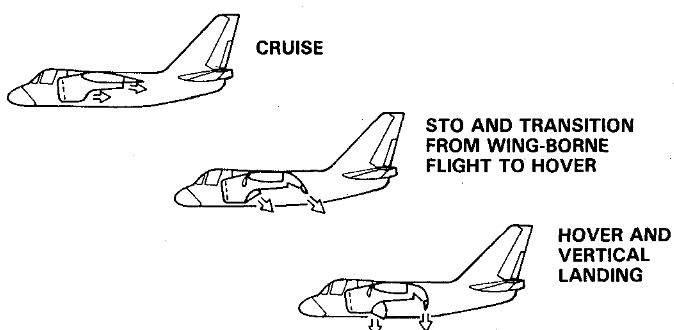

Fig. 4 **S-3 STOVL flight operation modes.**

Propulsion/Powered-Lift System Integration

The integrated TF34 and AIBF/VT powered-lift system for the S-3 STOVL is illustrated in Fig. 3. Note that the engine fan airflow is split into two streams. One stream powers the AIBF system and the other is mixed with the core engine flow to power the forward nozzle, providing a two-poster hover system.

The engine is mounted at zero incidence relative to the horizontal reference line. It is mounted considerably farther forward compared to the installation on the S-3A due to pitching moment requirements for hover operations. The inlet is of the "zero length" type with slotted lips to reduce inlet distortion during the powered-lift mode of operation. For this design study, two different power splits were evaluated; the more promising 70% forward nozzle/30% AIBF power-split results are discussed. For the powered-lift modes, the jet-flap exit area and the forward nozzle area are adjusted to match the design power split. During normal cruise flight, the jet-flap exit is closed. The upper BLC slot adjustment element, located at the knee of the main flap, is used to optimize BLC blowing to maintain an attached airflow over the flap during STO and transition from wing-borne flight to hover. During cruise flight, it operates as a conventional spoiler.

Figure 4 illustrates the AIBF/VT system operating in various flight modes. In the conventional flight mode, the exhaust streams are directed straight aft without one of the streams entering the trailing-edge flap. In the STO mode, the jet-flap and the forward nozzle flows are deflected 30 deg at liftoff. For the VL and hover modes, the jet-flap and the forward nozzle flows are turned vertically down.

Weight and Balance

The weight and balance data for the S-3 STOVL configurations are very similar to those of the S-3A. The major differences are due to the addition of two TF34 engines and modifications to the wing leading- and trailing-edge flaps. In addition, all of the ASW-associated equipment is removed and replaced by a 5000-lb general cargo/mission equipment weight provision. An empty weight comparison between the S-3A and S-3 STOVL is presented in Table 3. A weight saving of approximately 20% is assumed to be realizable by the use of composite structural materials for the wing.[6]

The axial placement of the engines is determined by balancing the pitch moment about the aircraft center of gravity (c.g.) during critical hover operations. To achieve the same balance as the S-3A, the STOVL payload is strategi-

Table 3 Empty-weight comparison

	Weight, lb	
	Basic S-3A	S-3 STOVL
Wing[a]	4841.1	3872.8
Tail	1188.8	1188.8
Body	4935.8	4935.8
Landing gear	1645.4	1645.4
Surface controls	1555.0	876.0
Nacelle	763.0	1526.0
Propulsion[b]	3371.3	6742.6
Auxiliary power plant	233.1	233.1
Instruments and navigation equipment	168.4	217.6
Hydraulic	376.1	376.1
Electrical	725.6	725.6
Electronics	4173.5	897.1
Armament	268.2	0.0
Furnishings and equipment	824.5	824.5
A/C and anti-ice	925.9	925.9
Auxiliary gear	275.1	275.1
Weight empty[c]	26,270.8	25,262.4

[a]S-3 STOVL has 20% weight saving with composite wing. [b] S-3 STOVL requires four engines versus two for S-3A. [c] S-3 STOVL does not include ASW mission equipment.

Table 4 Takeoff gross weight comparison for ASW mission

	Weight, lb	
	BASIC S-3A	S-3 STOVL
Weight empty	26,270.8	25,262.4
Useful load	14,965.0	14,965.0
Crew		
Fuel		
Oil		
Equipment		
ASW equipment	0.0	5,000.0
Gross weight	41,235.8	45,227.4

cally placed to shift the aircraft c.g. to 20% of the mean aerodynamic chord (MAC) to simplify the conventional-flight stability and control requirements. Figure 5 shows the c.g. diagram for the S-3 STOVL with a simulated 5000-lb ASW payload. The envelope is well within the S-3A design limits.

For performance analysis purposes, different S-3 STOVL missions are simulated by varying the payload. Table 4 presents the takeoff gross weight calculated for the ASW mission. The uninstalled thrust of the TF34 engine used is 9275 lb and 8256 lb at sea level standard-day and hot-day conditions respectively. Available test data show that AIBF duct loss is approximately 5%. No loss is assumed for the forward nozzle, but usual installation losses are assumed. This results in the hover limits shown in Fig. 5.

Control Techniques

The proposed control techniques for STO and hover are summarized in Fig. 6. For STO, pitch control after liftoff (design liftoff airspeed is 60 knots) is maintained by the horizontal tail in the conventional manner. Yaw control is provided by a double-hinged rudder. Prior to 60 knots, nosewheel steering is used. Asymmetrical or differential control-flap deflections, asymmetrical aft-nozzle thrust, or a combination of these techniques is used to maintain roll control.

Hover pitch control about a design c.g. of 20% MAC is maintained by varying the forward and aft nozzle thrusts using area adjustment to obtain nose-up or nose-down moments. For off-design c.g. locations, the same method of thrust allocation is used to statically balance the aircraft.

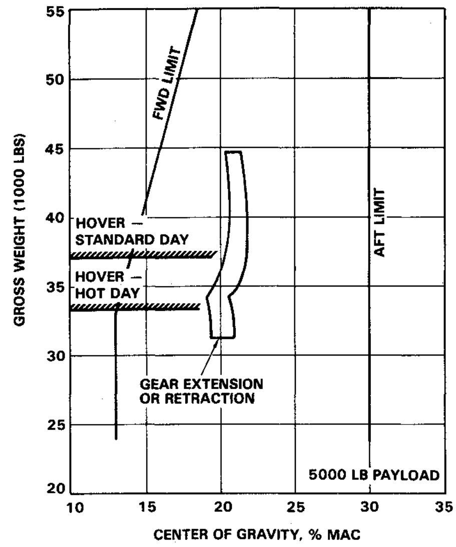

Fig. 5 Center of gravity diagram.

Roll control in hover is provided by moving the wing's center of pressure inboard and outboard. By maintaining a total constant nozzle area on both sides of the wing, the lift vector can be maintained constant. However, increasing the outer-wing AIBF nozzle area and decreasing the inner-wing nozzle area, while keeping the total area the same, moves the center of lift outboard. This creates a longer moment arm. By reversing the procedure on the other wing, a good rolling moment can be generated without an associated loss in lift.

To create yawing moment in hover, the thrust vectors are asymmetrically altered to obtain equal but opposite horizontal thrust components on each side of the aircraft. This can be achieved by increasing the forward nozzle deflection past 90 deg and increasing the control flap deflection on one side of the aircraft while decreasing the same on the other side.

The wing-borne or conventional flight mode is defined by the full retraction of the forward nozzle and the leading- and trailing-edge flaps to their neutral positions. In this flight mode, yaw and pitch controls are maintained by the rudder and horizontal tail, as in the S-3A. Roll control, however, is by means of the control flap, which now acts as a segmented aileron. The speed brakes on the S-3A are replaced by the AIBF upper BLC slot-adjustment element.

Due to the limited scope of the preliminary evaluation of the S-3 STOVL configuration, engine-out controllability is not investigated. However, with the redundant control techniques available to the AIBF/VT S-3 STOVL configuration, the problem can be minimized.

Deck Performance

To estimate the STO performance of the S-3 STOVL aircraft, unpublished Lockheed AIBF aerodynamic data derived from Ref. 7, S-3A flight test data, and vectored thrust data from Ref. 8 are used. The following takeoff procedure is assumed: 1) after completion of all warm-up procedures, the aircraft is configured with the forward nozzle undeflected for maximum acceleration and the main flap deflected 30 deg; 2) the control flap is positioned −30 deg to minimize drag and maximize acceleration; 3) at 50 knots, the forward nozzle rotation is initiated to a 30-deg down position; and 4) at 60 knots, the fast-acting control flap rotates through 60 deg to its liftoff position of 30 deg. For a 70/30 design power split, the takeoff deck roll at standard-day and hot-day conditions are calculated using a computer program developed at the Naval Air Development Center,[9] and the results are presented in Fig. 7. This figure shows that for takeoff gross weights up to 55,000 lb, the S-3 STOVL unassisted deck roll is less than 300 ft.

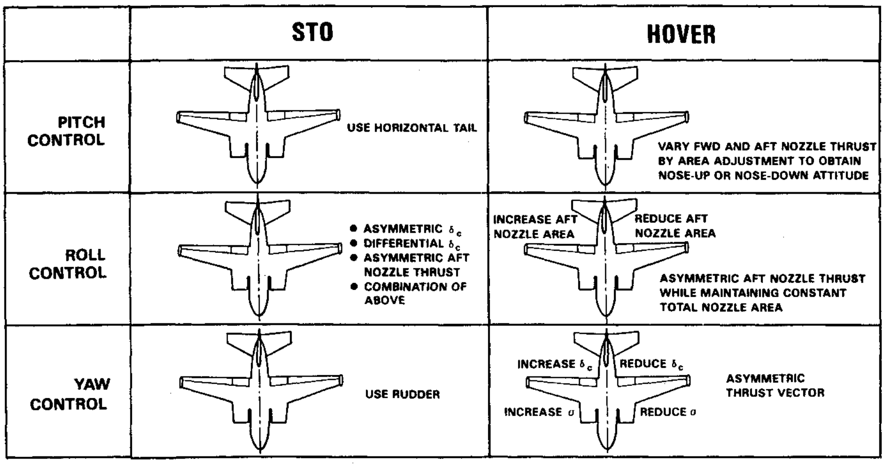

Fig. 6 STO and hover control techniques.

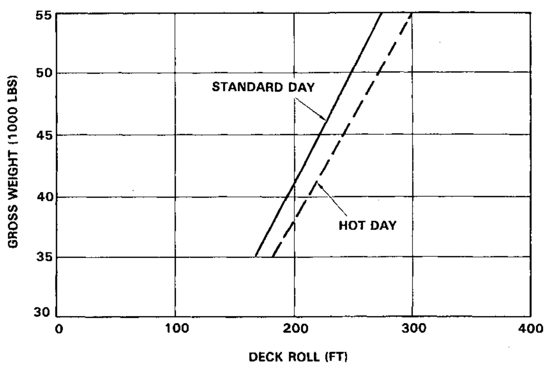

Fig. 7 STO performance.

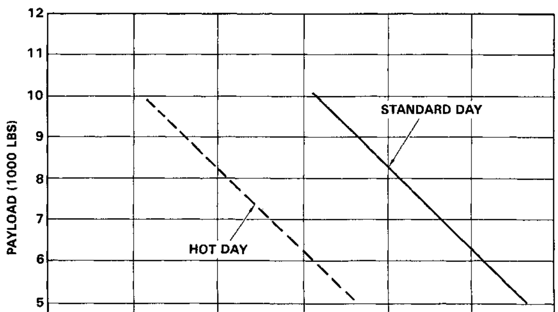

Fig. 8 Hover performance.

Due to the large downwash angles associated with the very high lift coefficients produced by the AIBF powered-lift system during STO, the horizontal-tail trim range required for the S-3 STOVL is +25.0 to −11.0 deg to cover all possible takeoff trim requirements. Since the trim range of the horizontal tail of the S-3A is from +1.0 to −9.0 deg, modification to the existing S-3A trim system is required.

Figure 8 presents the payload vs the minimum fuel weight to hover for the S-3 STOVL for standard-day and hot-day conditions. Note that all of the thrust produced by the engines is used for lift generation and is not required for control, due to the unique control features of the AIBF/VT system. This figure shows that on a standard day, hover with a 10,000-lb payload is feasible with approximately 1300 lb of fuel in reserve. On a hot day, however, operation is degraded to a 6000-lb payload with 1300-lb of fuel remaining.

Mission Performance

High-speed flight performance calculations require a combination of accurate aerodynamic and propulsion data. For this study, S-3A data were modified to reflect the external changes to the S-3 STOVL configuration. Mission performance for a variety of missions is generated from these data.

The cruise drag polar is developed by adding an incremental drag of 66 counts to the S-3A drag polar for the S-3 STOVL configuration. This incremental drag is a result of a drag buildup. The propulsion inputs for analyzing S-3 STOVL performance are based on using the installed TF34 engine performance derived from th S-3A installation.[10]

All S-3 STOVL mission performance calculations were performed using the Modular Segmented Task Oriented Mission Program (MSTOMP),[11] developed jointly by the Naval Air Systems Command and Naval Air Development Center, which supersedes all previous performance programs used by the Navy. The mission performance is based on all four engines operating continuously. This makes the S-3 STOVL over-powered in the high-speed regime, which requires a lower power setting. It also causes the engines to operate at higher specific fuel consumptions than when operating with two engines, substantially reducing the mission capability.

Four missions (COD, AEW, ASW, and tanker) for payloads of 5000, 7500, and 10,000 lb are evaluated for the S-3 STOVL. Warm-up and takeoff fuel consumption is simulated by 2.5 min of maximum power. Fuel reserves for landing consist of 5% of internal fuel (660 lb) plus 20 min of flight time at 10,000 ft at maximum endurance rating (approximately 900 lb). The total reserves are therefore approximately 1500 lb. Figures 9–12 present the results of the computer simulations and comparisons with the performance of CTOL aircraft for the same missions.

For the Carrier On-board Delivery (COD) mission, the S-3 STOVL design demonstrates superior range performance compared to the C-2 aircraft.[12] With the addition of a typical in-flight refueling of 3000 lb, the S-3 STOVL easily meets the current Indian Ocean mission requirements (Fig. 9).

Figure 10 presents a comparison of the aircraft on the Airborne Early Warning (AEW) mission. In this figure, the S-3 STOVL is compared with the E-2C,[13] and the results show better than equal performance for the STOVL at a higher altitude, resulting in a greater radar horizon. Note that the S-3 STOVL performance does not include a drag increment for a top-mounted rotary dome antenna, because its conformal antenna arrays are assumed to be mounted either on the fuselage, wings, or both.

A comparison between the S-3 STOVL and the S-3A aircraft[14] in the antisubmarine warfare (ASW) mission is presented in Fig. 11. For equal mission load and a representative radius of action, the S-3 STOVL suffers considerable

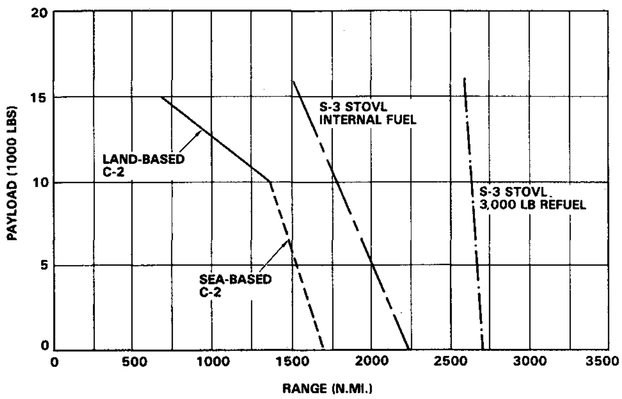

Fig. 9 COD mission comparison.

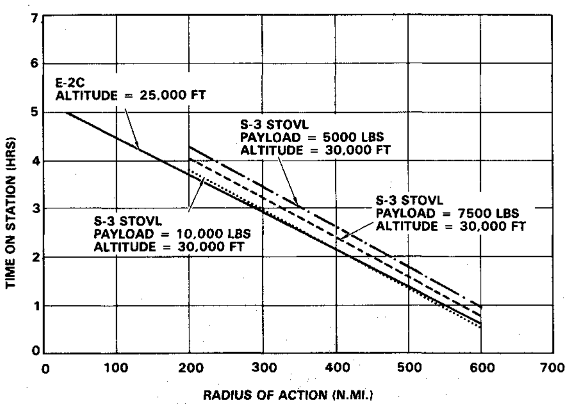

Fig. 10 AEW mission comparison.

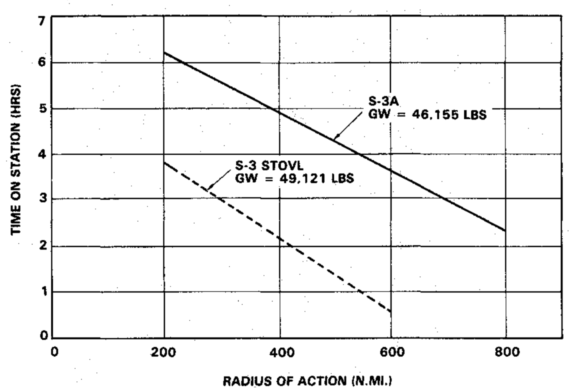

Fig. 11 ASW mission comparison.

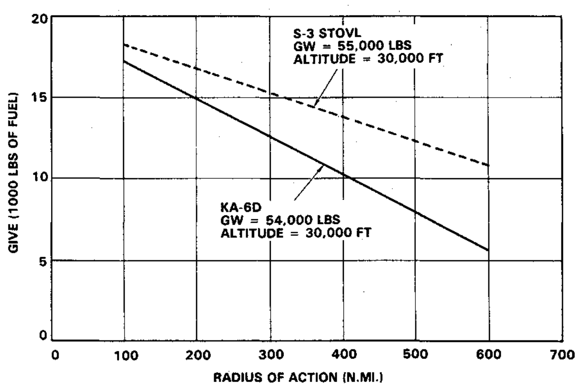

Fig. 12 Tanker mission comparison.

time-on-station performance penalties compared to the S-3A. This is due to the present assumption of operating all four engines continuously. To improve cruise and loiter fuel consumption, two of the four engines may be windmilled or stopped completely. Further studies are required to determine the tradeoff between windmilling drag and inlet spillage drag.

Figure 12 presents a tanker mission comparison between the S-3 STOVL and the KA-6D.[15] The S-3 STOVL assumed a tanker package weight of 5000 lb with a maximum takeoff weight of 55,000 lb. For a 30-min on-station time and a mission radius of 300 n.mi., the STOVL provides a 3000-lb fuel offload advantage over the KA-6D.

Conclusions

A conceptual design study has been conducted on a realistic approach to providing medium-speed, multimission STOVL capability for the Navy. This approach is based on a minimum-cost modification of the S-3A aircraft. The results show that this is a promising approach. From deck performance calculations and evaluations of four missions for the S-3 STOVL, the following are indicated:

1) For a TOGW up to 55,000 lb, the S-3 STOVL requires less than 300 ft deck roll for unassisted takeoff at S.L., hot-day, zero WOD conditions. At S.L., standard-day conditions, vertical hover with a 10,000-lb payload is feasible with approximately 1300 lb of reserve fuel.

2) For equal payload, the range performance of the S-3 STOVL for the COD mission is superior to the C-2a and meets current Indian Ocean mission requirements with a typical in-flight fuel transfer of 3000 lb.

3) Compared with the E-2C for the AEW mission, the S-3 STOVL shows better than equal time-on-station performance at a higher radar-search altitude than the E-2C.

4) In the tanker configuration, the S-3 STOVL's estimated fuel-offload advantage over the KA-6D is approximately 3000 lb at an operating radius of 300 n.mi.

5) Configured for the ASW mission, the S-3 STOVL suffers considerable time-on-station performance penalties compared to the S-3A. To improve cruise and loiter fuel consumption, two of the four engines may be windmilled or stopped completely. This requires further studies.

Acknowledgments

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