Enabling technologies for a centre-line tiltrotor

B. Burrage
bob.burrage@ntlworld.com
Rotorcraft Operations
Oxfordshire, UK

ABSTRACT

The success of the MV-22 Osprey has created the opportunity for a new design of gunship, tailored to the task of escorting it, an opportunity identified by many. Existing and emerging rotorcraft technology does not appear to have the complete capability, so this centre-line tiltrotor approach is aimed specifically at the escort duty.

The mission is taken to be escorting the MV-22 throughout a land assault (Marine Corps), to provide cover while the MV-22 is on the ground at the landing zone, and to still have useful capacity for diversions. To meet this task this Escort concept stays with the same core physics of tilting rotors plus fixed wings of the Osprey, but re-configured for gunship duties. The rotors are removed from the wing tips to mount them on the aircraft centre-line as inter-meshing rotors tilting back one-at-a-time, to act as pusher props in the aeroplane mode. The merits and concerns of this approach are discussed.

The study first reviews present tiltrotor technology and how that may develop. It then reviews what may be achievable from the centre-line tiltrotor configuration, the targets needed in key design parameters and design sensitivities, defining what the enabling technologies must achieve for the Escort. In hover, key areas are rotor disk loading and figure of merit, and also the rotor blockage caused by the fuselage and wings. In winged flight, the proprotor propulsive efficiency and the aircraft lift-over-drag are key, and fundamental to the feasibility of any tiltrotor concept, there is the all important transition process.

At this conceptual stage of the Escort, the transition process stands out as the dominant risk, and one that touches on all the others, so it was decided to build and flight test a model. The flight test programme plans are described and initial flight results reported.

Paper No. 3756. Manuscript received 12 August 2011, revised version received 9 June 2012, accepted 26 July 2012.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

NOMENCLATURE

A	effective area of the rotors
AR	aspect ratio of wings
$bl\%$	% blockage of the rotors
$cp\%$	% control power margin
C_d	wing download coefficient
$C_{D,0}$	aircraft drag coefficient at zero lift
$C_{t/\sigma}$	blade loading
CTOL	conventional take-off and landing (aeroplane)
d	separation of hubs of overlapping rotors
e	Oswald efficiency of a wing
D	aircraft drag
DL	disk loading of a rotor
EEv	vehicle energy effectiveness
FCC	flight control computer
FCS	flight control system
FM	hover figure of merit
FUL	fixed useful load
HOGE	hover out of ground effect
HP_{max}	maximum power available to the transmission
ISA	International Standard Atmosphere
kg	kilogrammes
kn	knots
L	aircraft lift
L/D	aircraft lift to drag ratio
LH	left hand (rotor etc)
LZ	landing zone
MTOW	maximum take-off weight
nm	nautical miles
PL	power loading of a rotor
R	rotor radius
RH	right hand (rotor etc)
rpm	revolutions per minute
S	wing planform area
sfc or SFC	specific fuel consumption
TO_{fuel}	fuel available from take-off
TPP	tip path plane of a rotor
TCL	thrust control lever
UAV	unmanned aerial vehicle
VTOL	vertical take-off and landing
W	aircraft weight
W_{empty}	aircraft empty weight
W/S	wing loading
vi	induced flow at rotor
vh	induced flow at rotor in hover
V	relative wind

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Greek symbols

ζ	transmission losses
η or ηp	propeller efficiency
θ	collective pitch
θt	θ at the blade tip
κ	lift related drag factor
ρ	air density
σ	effective solidity of the lifting area
∞	suffix indicating settled values at infinity

1.0 INTRODUCTION

The success of the MV-22 Osprey has created the opportunity for a new design of gunship, tailored to the task of escorting it. The Osprey is a medium lift troop transport with the unique combination of range and speed that out-performs all existing helicopters, whether transports, utilities or gunships: there isn't a gunship suitable to be its escort. So the concept discussed here is a compact centre-line tiltrotor aircraft designed to have the agility, speed and range that would be needed.

The concept of a gunship tiltrotor was described in anti-helicopter role at an AGARD conference in 1981[(1)], was addressed in 1986[(2)] as part of high speed tilt rotor studies, the need raised in 1996[(3)], and in 2004 when it was reported[(4)] that 'The Marine Corps' top aviation officer has asked Bell Helicopter Textron Inc. to study arming its executive jet sized BA609 tilt-rotor aircraft as an Escort for the V-22 Osprey tilt-rotor troop transport'. No doubt the need has been discussed many times since as the Osprey programme progressed.

The centre-line tiltrotor concept arose from the determination to retain the advantages of range and speed achieved by the V-22 Osprey, in a more compact layout by moving the proprotors from the aircraft's wing tips to mount them on its centre-line. This approach was envisaged to be suited for military use in a light to medium utility, search and rescue, scout or gunship role, for civil use in a wide range of emergency, media, surveillance, tourism and passenger transport, and unmanned as a remotely piloted vehicle of micro size and upwards.

The purpose of this paper is to review the enabling technologies necessary for this centre-line tiltrotor concept to perform the role of armed escort for the V-22 Osprey.

2.0 ESCORT DESIGN

2.1 Background: XV-15, MV-22, AW-609

Tiltrotor aircraft combine the advantages of range and speed of turbo-prop aeroplanes with the advantages of vertical take-off and efficient low-speed flight of helicopters. These advantages are being exercised on a daily basis by the USAF special operations forces, and the US Marine Corps who have proven the worth of the V-22 Osprey in Afghanistan and in humanitarian missions in Haiti and elsewhere. In many such situations conventional airfields are not available, and helicopters may not have the range or speed vitally needed.

The technology base for present tiltrotor designs was established in the 1960s and early 70s when major issues such as aeroelastic stability, performance and control had to be mastered. The resulting technology was most impressively demonstrated by the Bell XV-15 tiltrotor research

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press



Figure 1. XV-15 on a VTOL stand at NASA Dryden, October 1980[5] (pic NASA).

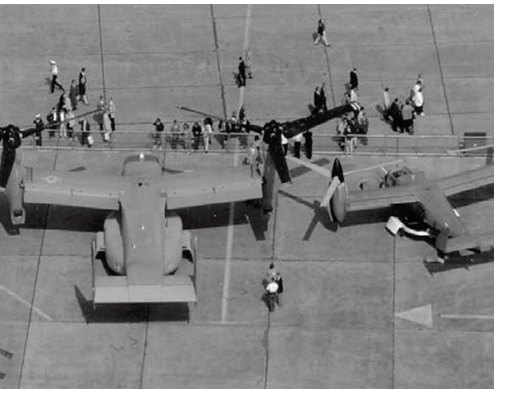


Figure 2. Bell-Boeing V-22 dwarfing the XV-15 (Ref. 6, Bell Photograph 042900).

program, initiated in 1973 with joint Army/NASA funding as a 'proof of concept', or 'technology demonstrator'. Figure 1 shows the XV-15 on a VTOL stand at NASA Dryden.

Aircraft development, airworthiness testing, and the basic 'proof of concept' testing were completed in September 1979[6].

By April 1983 Navair had announced the first contract for the tiltrotor to meet their JVX requirement: this was the start of the V-22 Osprey. Figure 2 shows the Bell-Boeing V-22 alongside the XV-15 research aircraft at the 1995 Paris Air Show, and by 1996 the full scale development programme[7] was showing that the concept and technology was holding good. On 14 May 1999 the first production V-22 Osprey was delivered to the US Marine Corps[6].

After the Herculean effort and determination by all involved, the United States Marine Corps fielded the Osprey in 2007. By May 2011 the Marine Corps MV-22 and the Air Force Special Operations Command (AFSOC) MC-22 had achieved 100,000 operational flight hours in combat and humanitarian missions.

Of course the learning process is a continuous one, the next major step being completion of certification of the AgustaWestland AW609 tiltrotor for civil applications.

Looking forwards, the enabling technologies of present tiltrotors will benefit from the steady progress in all the technologies on which the fixed wing and rotary wing communities depend. Some of those will read across directly, others must be adapted to the priorities of tilt rotor aircraft where technologies must operate satisfactorily in dual roles, combining rotary and fixed wing functions in a single implementation.

The foremost example of the dual role is the proprotor which acts as a rotary wing in helicopter mode and as a propeller in aeroplane mode. Proprotor efficiency is central to determining the useful payload/fuel budget that can be lifted at take-off in the helicopter mode, and in the winged flight mode how efficiently that budget can be used. In their paper on the aerodynamic challenges in optimising high efficiency proprotors[8]. Leishman and Rosen characterise efficiency goals in terms of figure of merit, FM, for the proprotor in hover, and propulsive efficiency, ηp, when acting as propeller. Their comprehensive review and analysis of the trade between these and other key parameters shows the space for possible improvement and the challenges and issues involved.

Another example of dual roles is that of the power plant. Shaft horse power requirements are very similar across the range (Fig. A-12 of Ref. 6), however the operating rpm will be different. The proprotor is operated more efficiently at lower rpm in the aeroplane mode so this lower rpm combined with the transmission torque limit in fact determines the maximum allowable power.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

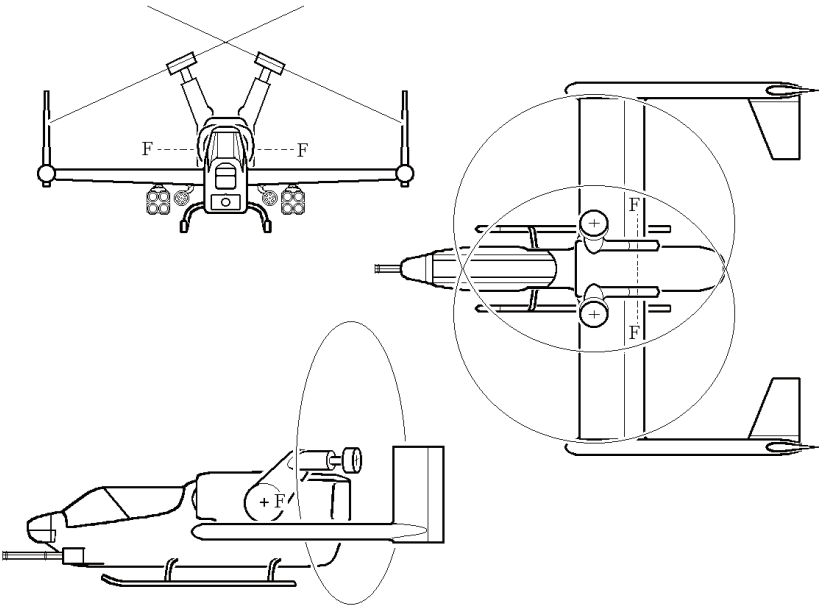


Figure 3. Two views of the Escort in the hover mode and one in cruise.
The meshing rotors are tiltable about the F-F axis.

If the transmission is designed for max power in aeroplane mode then it is off design for the helicopter mode, and vice versa. Similarly the power turbine operates at these dual speeds. All rotorcraft are likely to benefit from variable rotor speeds, so it is reasonable to hope that tiltrotors can share and participate in improving these engine and transmission enabling technologies.

2.2 Centre-line tiltrotor

The advantages sought for centre-line tiltrotors, as for present tiltrotors, are to combine the range and speed of turbo-prop aeroplanes with the vertical take-off and efficient low speed flight of helicopters. The same physics of the XV-15, MV-22 and AW609 tiltrotors is proposed, namely wings for efficient aeroplane flight and proprotors that tilt from providing lift in helicopter mode to become propellers to provide propulsion in aeroplane mode.

Further advantages are sought: to achieve a more compact and agile tiltrotor, where the forward field of view and fire is freer, where wing optimisation is unconstrained by bearing the rotors, transmission and nacelles, and where the extremities of the aircraft in helicopter mode are static rather than rotating blades.

The particular design solution[9] considered here is for a centre-line tiltrotor, tailored to the formidable task of escorting the MV-22 throughout its mission. The proposed layout is shown in Fig. 3 and a proposed specification shown in Table 1.

The Escort's two meshing rotors are mounted on the centre-line of the fuselage. They tilt back for cruise, give superb field of view for crew and sensors, and a wide field of fire for weapons and countermeasures. Having meshing rotors that tilt back gives a very compact design.

The suite of controls available to the Escort's flight control system is assumed to be similar to the MV-22: cyclic, collective and tilt for rotary wing, primary and secondary controls surfaces for fixed wing mode. An important addition is articulation of the leading portion of the main wings.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

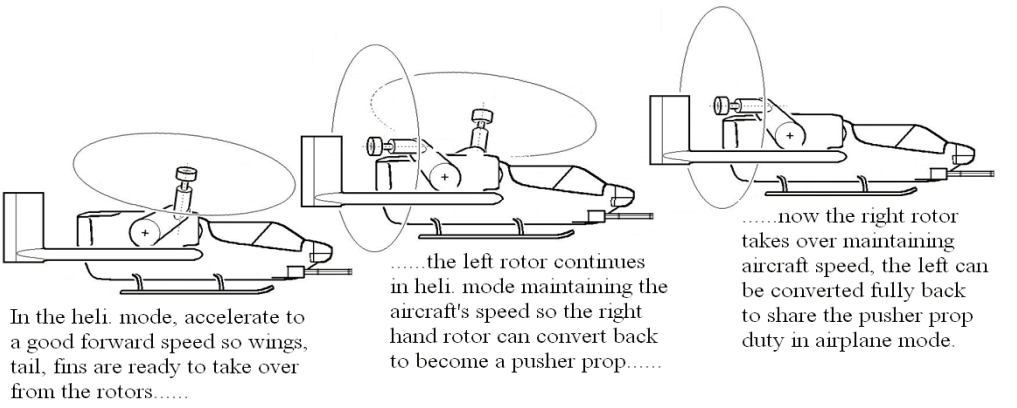


Figure 4. The centre-line tiltrotor is shown converting from helicopter to aeroplane mode.

Unlike present tiltrotors where the proprotors tilt forward to become tractor propellers, this centre-line layout requires that they tilt back to become pusher props. This means their thrust must be reduced to zero during transition, otherwise they act as airbrakes, and reversed only when fully back. So collective pitch has to be reversed, and if the blades are twisted then twist has to be reversed as well.

The decision was taken to convert the rotors one-at-a-time so that continuity of propulsion could be retained, and this led to meshing rotors to allow this process, see Fig. 4.

The result is a compact design.

Table 1 shows the proposed specification for the Escort in comparison with the assumed characteristics of the MV-22. It shows two important differences proposed for the Escort, maximum altitude for hover out of ground effect, and mission radius.

The Escort should always be able to hover higher than the Osprey in order to provide cover from above. To this end the Escort may appear over powered, however it is better to flat rate a powerful engine so that best use is made of the torque-limited transmission, than struggle to extend the altitude capability of lesser powerplant.

The higher mission radius of the Escort arises from the perceived need to stay with MV-22 throughout a mission, for example land assault, that must include at least the endurance to provide cover at the landing zone while the MV-22 is on the ground, and ideally have the additional endurance to undertake a significant diversionary task. So the Escort is planned to have better range than the MV-22.

One problem is that the Escort's proprotors are expected to be less efficient in hover and in cruise than those of the MV-22, so this must be remedied by other aspects of the Escort design. Articulation of the wings to align with the rotor downwash to reduce rotor blockage should offset its proprotor deficiency in hover. The greater freedom in wing design (no nacelles or rotors at the wing tips) should allow a better lift to drag ratio to be achieved and balance the lower efficiency of its proprotor in cruise. Finally, the fuel carried by the Escort, as a fraction of its MTOW, is planned to be higher than that of the MV-22. In combination these should provide the range needed.

To investigate the Escort's proposed design in more detail, the land assault mission is taken as the baseline.

2.3 Baseline mission: land assault

On an MV-22 mission[7], for example the Land Assault — Troop Lift (Marine Corps), the Escorts must protect the MV-22s every step of the way there and back, and especially at the landing zone, LZ.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Table 1
Comparison of the MV-22 and the proposed Escort**

	MV-22**	Escort
Deck area, ft × ft	83 × 58	36 × 32
Field of view/fire	good	superb
Engines, max hp	2 × 6,150	1 × 6150
MTOW, lb	52,600	19,500
Empty weight, lb	35,300	13,300
Service ceiling, ft	25,000	25,000
HOGE, max, ISA, ft	5,400	6,400
Max cruise, sea level, kn	250	250
Mission radius, nm	230	285

** *Brochure, or author's estimate not validated by manufacturers*

Table 2
Simplified fuel usage model of a land assault mission for the MV-22**

	Δt	EEv_{nm}	EEv_t	Load	Aircraft	Fuel	nm
Start of mission	0	0	0	5,760	47,000	5,940	0
Outward cruise	57·5	4,713	1,178	5,760	47,000	3,701	230
LZ loiter	15	0	1,249	5,760	44,760	3,167	230
LZ hover	5	0	674	5,760	44,226	2,840	230
Return cruise	57·5	4,713	1,178	0	43,899	748	460
End of mission	0	0	0	0	36,048	748	460

** *Brochure, or author's estimate not validated by manufacturers*

Landing zone duties would be scouting, suppressing hostile fire to clear a window for the troop insertion or extraction, acting as spotter for other providers of air cover, and providing communications or related support. The Escort should have a contingency reserve, so that it can execute a useful diversion in addition to fully supporting the planned MV-22 mission. A gunship escort that has the speed but lacks range, will penalise use of the MV-22 operating to its full capability.

Table 2 is a simple model of how fuel is burnt on the land assault mission envisaged for the MV-22. Δt is the time spent on a given segment, EEv is the vehicles energy effectiveness defined in Equation (4) below, expressed as EEv_{nm} when scaled in nautical miles, nm, or EEv_t as its equivalent scaled in minutes.

From having taken off, the outward cruise takes nearly an hour and then the MV-22 has to loiter for 15 minutes waiting for a safe window to land, spends five minutes at the landing zone hovering, landing and offloading the 24 troops, and taking off for the return leg of the mission. That is estimated to take a further 58 minutes to return to base, landing with just over 20 minutes of fuel reserve at cruising speed.

Table 3 is the corresponding fuel usage model for the Escort providing cover for the MV-22 throughout the land assault mission envisaged in Table 2. The outward leg broadly matches the MV-22's but at the landing zone almost as much fuel is assumed for duties in hover, spotting, laser designation or similar, as assumed for loiter. Having provided cover for the MV-22 throughout the

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Table 3
Fuel usage of the Escort on the Table 2 land assault

	Δt	EEv_{nm}	EEv_t	Ordnance	Aircraft	Fuel	nm
Start of mission	0	0	0	2,500	18,921	2,686	0
Outward cruise	57·5	4,993	1,248	2,500	18,921	1,834	230
LZ loiter	20·4	0	1,323	1,500	18,069	1,558	230
LZ hover	10	0	714	500	16,792	1,324	230
Return cruise	57·5	4,993	1,248	500	15,559	623	460
Divert	13·8	4,993	1,248	500	14,859	460	515
Divert hover	3·5	0	714	0	14,695	388	515
return	13·7	4,993	1,248	0	14,123	234	570
End of mission	0	0	0	0	13,969	234	570

Table 2 mission, the Escort still has 500lb of ordnance and sufficient fuel for a 110 nautical mile diversion including five minutes hover at the diversion target zone, a total diversion capability of 31 minutes.

The usefulness of Tables 2 and 3 lies not in their design accuracy, they are too much simplified for that, but in their use to illustrate 'what-if' scenarios and sensitivity analysis where the effects of key parameters can be investigated. So the formulae used are described next and then used to show sensitivity to some of the some of the design parameters for the Escort.

2.4 Formulae used

To simplify the estimate of fuel usage on the assault mission, the fuel available for the mission was assessed just once at take-off, assuming hover out of ground effect, and ignoring fuel usage up to that point. For the rest of the mission fuel usage was assessed using the Breguet cruise formula[10] for winged flight, but adapted to represent other modes as needed.

The equation for the fuel available from take-off, TO_{fuel} is:

$$TO_{fuel} = \text{MTOW} - W_{empty} - \text{FUL} - \text{ordnance-reserve} \quad \ldots (1)$$

TO_{fuel}, is determined by the maximum take-off weight (MTOW) less the Escort's empty weight W_{empty}, and the fixed useful load (FUL), i.e. crew, unusable fuel and oil etc, and the ordnance load and the mandated reserve of fuel. These parameters have direct impact on whether there is enough fuel for the mission, and are dominated by the difference between two large numbers, MTOW and the empty weight.

The Escort's empty weight is estimated from that of the AH-1Z, of which about a third needs to be updated to the new wings, empennage, twin transmission and rotors, and powerplant specific to the Escort.

$$W_{empty} = k_0 + k_1 R + k_2 HP_{max} \quad \ldots (2)$$

Appendix A shows how the estimates were made and estimates the constants k_0, k_1, k_2 for a locally linear approximation.

The equation for MTOW shows the effect of key design parameters on how the maximum available power, HP_{max}, is used to achieve take-off at the MTOW. Losses in the transmission, ζ,

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

and in the rotors, represented by rotor figure of merit (FM), and the effective area of the rotors, A, and the ambient air density, ρ, determine what thrust the rotors can deliver. However the wings and fuselage block a percentage of thrust, $bl\%$, and not all the thrust capability should be used just to take-off: the Escort needs a useful margin, $cp\%$, to provide control power and manoeuvrability immediately from take-off.

$$MTOW = (1 - 0{\cdot}01\ bl\%)/(1 + 0{\cdot}01\ cp\%)\ (2A(550.\zeta\ HP_{max})^2\ FM^2\ \rho)^{(1/3)} \quad \ldots (3)$$

Take-off provides the initial conditions for Tables 2 and 3 which then estimate weight changes and how efficiently the fuel is used throughout the different segments of the mission, where EEv is the vehicle energy effectiveness term in the Breguet range formula[10], modified as below

$$EEv = (L/D)/\text{sfc}\ \eta\ \zeta \quad \ldots (4)$$

$$\text{range} = EEv\ \text{Log}[W/(W - \text{fuel})] \quad \ldots (5)$$

EEv is determined by the aircraft lift-to-drag ratio, L/D, by the proprotor efficiency acting as propellers η, the specific fuel consumption of the powerplant, sfc, and the transmission losses, ζ. EEv is used in two forms, EEv_{nm} to estimate range in nautical miles, and EEv_{min} to estimate endurance in minutes. Best estimates of these parameters were used for cruise, then factored for hover endurance and for loiter range and endurance by scaling from XV-15 rotorshaft horsepower versus calibrated airspeed (Fig. A-12 of Ref. 6).

Table 4 shows the values of these and other design parameters assumed for the baseline land assault mission.

The end result of these estimate would be that the Escort would be able to cover the MV-22 throughout the 230nm land assault mission, and have the range to add a 33 minute diversion.

The next questions are how sensitive is the Escort's capability to the assumptions and parameter values used, and what are the enabling technologies involved.

2.5 Sensitivity analysis

The baseline land assault mission of Table 3 of the Escort provides a suitable performance criterion: the endurance margin available for a diversion. So sensitivity is expressed here as the extra minutes of diversion in cruise obtained from improving a design parameter by 1%. Appendix B summarises the method used.

These parameters yield extra diversion time as follows:

- Rotor blockage reduced from 4·8% to 3·8% yields 13·4 minutes extra
- 1% weight reduction gives 4·9% more fuel, yields 8·5 minutes extra
- 1% increase in FM yields 8·5 minutes extra
- 1% in rotor radius R yields 7·2 minutes extra
- 1% improvements of η, L/D, ζ, or sfc yield 1·8 minutes extra

As a generalisation, parameters that affect the capability to lift fuel at take-off dominate 5:1those that affect the fuel efficiency over the rest of the mission. This provides a practical background for discussing the enabling technologies for the Escort.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Table 4
Baseline mission: assumed parameters

	MV-22**	Escort
Engines, max hp	2 × 6,150	1 × 6,150
Blade radius, *R* ft	19·04	12
Effective area, *A* ft^2	2,278	600
Blades/rotor	3	3
Effective solidity, σ	0·12	0·2
Blade loading, C_t/σ	0·15	0·12
Rotor figure of merit	0·81*	0·72
Rotor blockage, *bl*% lift	8·9	4·8
Control power, *cp*% lift	AH-1Z: 17·1**	16·4
Take-off weight, lb	47,000	18,920
Empty weight, lb	33,385	13,300
FUL, lb	1,464	435
Payload, troops or ordnance	24 troops	2,500lb
Fuel, lb	5,940	2,685
Cruise lift/drag, *L*/*D*	9	11
Cruise % max, shp	35	21
Cruise sfc, lb/shp/hr	0·42	0·42
Prop Efficiency, η	0·75*	0·65
Mission cruise, kn	240	240

** Baseline proprotor performance from the large rotorcraft study[14]*
*** Brochure, or author's estimates not validated by manufacturers*

3.0 ENABLING TECHNOLOGIES

The aerodynamics of fixed meshing rotors has a firm foundation in research, development, manufacture and extensive operational experience. Historically, the Kaman Huskie, and currently, the Kaman K-MAX provide practical benchmarks.

The principal features that distinguish the centre-line tiltrotor from that fixed mesh, non-tilting helicopter background are

- Wings and airframe configuration
- Rigid proprotors with high loading
- Differential longitudinal cyclic for yaw control
- Cruise thrust reversal as a pusher prop
- Separately tilting pylons

Those differences are large and so although there are bound to be useful lessons, the design of the Escort is much closer to present tiltrotor technology.

The sensitivity analysis of Section 2.5 gives a guide as to the benefit or loss from an increment in a design parameter. For mature technology the risk and cost of making an increment should be predictable as to what is acceptable for the benefit promised. However if there is novelty involved

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

it is not a smooth increment, it has become a step change that needs de-risking.

Transition is not incremental. There is substantial novelty and risk: the rotors are meshing and tilted back rather than forward, the tilting is asymmetric and one-at-a-time rather than symmetrically tilting together, all features that are novel to tiltrotors. So for Escort the transition process needs de-risking, whatever else.

With those thoughts in mind, here is an overview of the enabling technologies that the Escort requires in the specific area of performance at take-off, cruise, and transition.

This leaves many enabling technologies unmentioned, so an attempt at a list is made in Section 3.4.

3.1 Concerns

At IPLC in Philadelphia 2010, Dan Newman very kindly reviewed the centre-line tiltrotor paper[9] and gave the following informal list of issues:

Main issues

1. Twist reversal on rotors? Risk up
2. Symmetrical aerofoils? FM down
3. Trim during conversion? Drag of controls compensating for trim.
4. Thrust during conversion?
5. Loads and performance for wake into perpendicular rotor?
6. Controllable, reversible conversion

Minor issues

1. Rotor-boom clearance in cruise
2. Weapons plume in cruise into rotors
3. Countermeasures in cruise into rotors
4. Why field of view better than V-22?
5. Why no speed margin?
6. Weight for blade fold + wing stow? Download articulation?
7. Low aspect ratio wing
8. Rotors at zero NET thrust still generate out-of-plane loads (inflow)

The list is a valuable starting point for considering enabling technologies.

3.2 Take-off

The Escort's mission capability is largely defined by what it can lift at take-off, less its empty weight, (MTOW – W_{empty}) as described by Equations (1), (2) and (3). To prioritise changes in design parameters, the sensitivity analysis suggests that effects at take-off are five times more important to mission endurance than those for cruise efficiency.

MTOW

The design parameters that affect MTOW are: the rotor radius R and effective area A, the maximum power allowed by the transmission or by the powerplant HP_{max}, transmission efficiency

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

ζ, rotor blockage *bl*% and figure of merit *FM*, plus mainly operational parameters ρ, *cp*%, FUL and fuel reserve, all requirements that the design must accept. Assuming that present technology can provide proven choices only for *R*, *A*, HP_{max} and ζ that leaves the enabling technologies for proprotor figure of merit FM and blockage *bl*% to be assessed.

Empty weight

Appendix A shows some of the innumerable parameters that affect empty weight, and the sensitivity analysis shows the large impact that any increment in weight can have on the mission.

Right from the concept stage there is an unrelenting design battle to keep down the empty weight of an aircraft, a battle that continues over the complete life cycle. For the Escort it would be an important coup to be able to have two thirds of its empty weight as unchanged legacy from a mature project such as the AH-1Z or other gunship. This would de-risk two thirds of the potential sources of weight problems as well as de-risking their functionality.

Rotor blockage

Rotor blockage is a variable feast. In a dead flat calm it is a serious burden for hover. However, if a rolling take-off were feasible, or if there is a wind to point the nose into, the rotor downwash may not touch the wings and their contribution to rotor blockage has effectively been swept away. Nevertheless hover in a flat calm is taken to be one of the Escort's baseline design points.

In hover out of ground effect (HOGE), where the downwash from the rotors meets fuselage and wings, there is a download that must be set against the lift from the rotors. The term rotor blockage is used here to express that download as a percentage of rotor lift.

Stepniewski and Keys[11] report wind tunnel tests of downloads on a tiltrotor wing suggesting a wing with just flaps would have a drag coefficient, C_d, referenced to the flat wing, of 0·64. By contrast, if the wing can be aligned to the downwash the drag reduces to a C_d of 0·01.

On the MV-22 Osprey, flaperons are used to substantially reduce the download effect. The remaining download is significant and a worthy target for research[12].

On the Escort, the wing blockage is larger, so greater articulation of the surfaces would be needed. For example, the plan view in Fig. 3 shows axes E1 and E2 for rotation of the leading and trailing halves of the wing to align with the rotor downwash. In principle this should achieve the rotor blockage factor estimated in Table 4.

Blade aerofoil, twist and taper

The blades of present tiltrotors have optimised aerofoils, are tapered and highly twisted, to give a good figure of merit for helicopter mode and good efficiency in cruise, for example *FM* = 0·81 and η = 0·75 as Table 4[13,14]. In the transition sequence, see Fig. 4, the Escort's centre-line layout requires that the rotors tilt back to become pusher props and so collective pitch has to be reversed, and if the blades were twisted then twist would have to be reversed as well, a technology challenge.

Variable twist for full reversal would solve the problem but appears unproven so the Escort baseline assumes untwisted blades with a NACA 0012 symmetric aerofoil and targeting a lower *FM* = 0·72 and η = 0·65 to reflect this. To improve on the baseline performance, some options are

- Fixed, part twisted blades to favour take-off and accept the cruise penalty
- Controllable twist to suit actual flight conditions, partial or full, this should help both take-off and cruise
- Optimise blade taper and aerofoils

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Rotor swirl

The rotational energy in a helicopter wash may use 2% of power delivered to the rotor, or more for heavily loaded rotors in hover[15]. For the Escort, much of the wash from the two rotors is merged or the rotation of one wash blocks that of the other, so some rotational energy should cancel. This would lead to a proportional improvement in *FM* and presumably in propeller efficiency η as well.

Effect of rotor overlap and blade twist on *FM*

In hover, ideally twisted blades would provide a uniformly flat distribution of induced flow vi across the whole lifting area, and will tend to minimise the losses (Ref. 16, p 52). Real blades approach this ideal by using linear twist, and in the case of the MV-22 using bi-linear twist[17]. For the Escort the baseline proposal is to use untwisted blades, which unfortunately generate an induced flow pattern that is triangular, maximum at the rotor periphery and decreasing linearly to zero at the hub, and have a penalty of lowering the *FM*.

Studies of the effects of overlap on rotors that are substantially co-planar and flat are reported in Ref. 19 and analysed in Ref. 11 using a momentum plus blade element theory. To extend this work to the Escort it will be necessary to include both the effects of high levels of overlap and canting of the rotors.

3.3 Cruise

In the aeroplane mode the Escort's meshing proprotors are in the pusher prop position at the rear of the fuselage, between the twin booms, aft of the wings and ahead of the empennage see Figs 3 and 4.

The target *L*/*D* for the aircraft in this configuration at cruise is 11, which is a useful improvement compared to 9 assumed for the MV-22.

However the target for proprotor efficiency η at 0·65, is set lower than the 0·75 assumed for the MV-22 (Table 4) to give some margin for anticipated problems.

Considering the proprotor first, it is tilted back behind the fuselage and wings to operate in their wakes in pusher mode. Raymer[18] suggests that airframe turbulence and the pressure difference between the wakes above and below the wing cost a pusher propeller η some 2% to 5% efficiency. Also the blades for the baseline configuration of the Escort are untwisted, and this is expected to be a worse effect. Clearly if the highly developed MV-22 proprotors achieve η = 0·75 tilting forwards into clean air and using optimised blade aerofoils, taper and twist, then setting the Escort baseline target for η at 0·65 is in the right direction but will need to be treated with caution. Next considering the aircraft lift-to-drag ratio, the *L*/*D* for steady level flight can be estimated[10] from

$$L/D = \left(\frac{\rho_\infty V_\infty^2 C_{D,0}}{2W/S} + \frac{2\kappa}{\rho_\infty V_\infty^2} \frac{W}{S} \right)^{-1} \quad \ldots (6)$$

where *W*/*S* is the wing loading and, from the aircraft drag polar, $C_{D,0}$ is the aircraft drag coefficient at zero lift and κ is the factor for drag due to lift. Table 5 shows the values assumed for the XV-15, MV-22 and the Escort. The value of $C_{D,0}$ for the Escort assumes that it can achieve similar aerodynamic cleaness to the air combat fighter tiltrotor of Ref. 2. The estimates of κ assume the Oswald factor *e* to be 0·82, (Fig. 6, Ref. 7).

Applying the Table 5 data into Equation 6 for the MV-22, gives an *L*/*D* of 10·5 that is 1·5 better than believable, so an arbitrary 1.5 penalty has been applied to the *L*/*D* estimates for all three

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Table 5
Aircraft lift-to-drag data

	$C_{D,0}$	AR	$\kappa = 1/(\pi\, e\, AR)$
XV-15	0·056*	6·1*	0·032
MV-22	0·063*	5·5**	0·035**
Escort	0·049*	6	0·032

** NASA study, (Table 4, Ref. 2), **Aerodynamic development review, (Fig. 6, Ref. 7)*

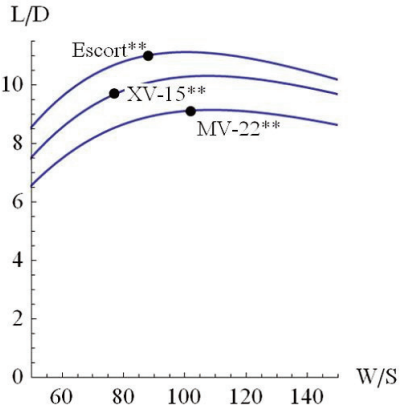


Figure 5. Aircraft lift-to-drag ratio *L*/*D* versus wing loading W/S. Points show cruise.
**Author's estimates using Equation (6).

tiltrotor aircraft in Fig. 5. The plots show the influence of wing loading *W*/*S* on *L*/*D*, and the points indicate cruise, assumed to be 240kn.

To meet the Escort target *L*/*D* of 11, the studies assumed $C_{D,0} = 0{\cdot}045$ which may or may not be compatible with the major use of legacy from an existing gunship. The wing aspect ratio of 6 seems achievable especially as the wings are no longer constrained to carry the large nacelles and rotors: so there should be design freedom to optimise wing shape and loading to achieve a good κ. The MV-22, AW-609 and XV-15 benefit from the end-plate effect of the nacelles, if necessary the equivalent for the Escort would be to consider winglets.

3.4 Transition: the principal challlenge

Flight control system

Before discussing transition it is important to have a baseline concept for the fly-by-wire flight control system (FCS).

If legacy technology were available for the Escort's FCS, the obvious candidates would be the MV-22 flight control computers (FCCs) and the suite of inceptors, sensors, effectors and links to other systems that the FCCs must serve. Starting from that legacy, the following are issues to be considered.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Control laws:
At this concept stage, there are two focuses on control laws (a) what is the minimum needed to demonstrate transition with the 10kg model described below and (b) the handling qualities of the full scale Escort.

For the 10kg model the approach is to schedule, mix and trim the pilot's control inputs in open loop fashion and to fly without stabilisation, no rate gyro feedback. When the test pilot is satisfied that the basic characteristics of the model are understood, then rate feedback is brought in and flight testing proceeds to the next issue.

For the full scale Escort, Liverpool University have assigned to Ross Willington the task of a first assessment of the centre-line tiltrotor in helicopter mode only, from hover to 80kn, as a final year project[21] completed Spring 2012. This is the project paper's Abstract: 'Rotorcraft Operations Ltd has proposed a concept for a novel tilt-rotor configuration, the Centre-Line Tilt Rotor (CLTILT), which provides the advantages of conventional tilt-rotors in a compact configuration. However, it is not known if the new configuration has any flight dynamics advantages over the standard tilt-rotor configuration. To address this, a FLIGHTLAB simulation of the Bell XV-15 has been modified to test the CLTILT configuration, in hover, as it might appear on a full-sized aircraft. Specifically, the dynamic stability of the CLTILT configuration has been compared to that of the XV-15. It was found that there is little difference between the CLTILT and XV-15 configurations in the longitudinal axis; however, in the lateral-directional axes, the CLTILT configuration has two clear advantages: crisper roll response and inherent spiral mode stability. These benefits, however, may yet be offset by a faster-acting Dutch roll mode which could degrade the handling qualities of CLTILT-configured aircraft.'

Returning to comparing the control approach for the Escort, assuming the MV-22 FCS as legacy, what follows is an overview.

Helicopter mode:
The controls, longitudinal cyclic for pitch, differential longitudinal cyclic for yaw, are expected to be the same, but roll is expected to differ by use of lateral cyclic rather than differential collective. Of the control algorithms and filters hopefully most will remain but with new data to reflect the differences in flight and structural dynamics. The secondary flight control of the flaperons on MV-22 may read across to controlling the inboard wings of the Escort if a single surface is used, however the baseline concept of two articulated surfaces is more complex.

Aeroplane mode:
It is assumed that the legacy FCS would be readily adaptable to the Escort for most aeroplane mode tasks.

Transition:
From a pilot's point of view, it is proposed that the Escort have the same transition control interface as the MV-22. It is assumed that on the MV-22, the thumbwheels on the crews' thrust control levers (TCLs) are used to control transition via proprotor nacelle angle. For each nacelle angle, the aircraft has a viable flight envelope within part of the tiltrotor's transition corridors. At any point in the transition the crew can choose to hold the nacelle angle, reverse or continue to the flight mode that suits.

For the Escort, it is proposed to use the same approach of thumbwheels on the crews' TCLs: at any point in the transition the crew can hold, reverse, or continue as required through the transition shown in Fig. 4.

Some possible differences are:

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

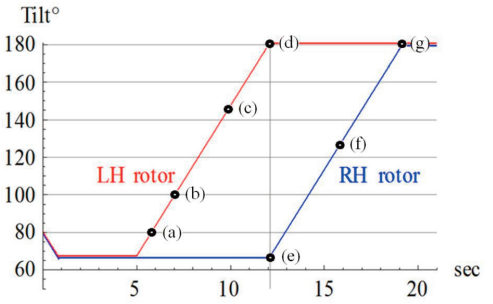


Figure 6. One-at-a-time tilting as used in a math model for the transition of Fig. 4. The text refers to points (a) to (g) to discuss airflow relative to the rotors as they tilt back to 180º.

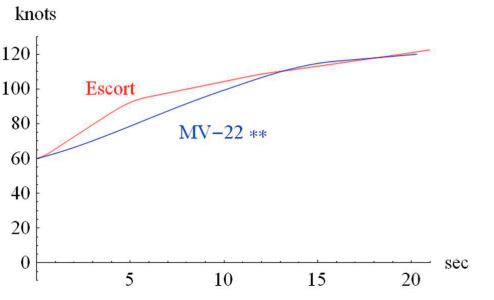


Figure 7. The Escort and the MV-22** (author's estimates) transitioning from 60kn in helicopter mode to about 115kn in aeroplane mode. Aircraft at minimum operating weights. See Fig. 6 for the control schedules used by the Escort.

- the display of tilt status for one-at-a-time tilting
- a pilot has requested means to select that LH or RH goes first to suit flight situation

The Escort's FCCs must achieve transition using a suitable tilting strategy, for example as shown in Fig. 6.

Figure 7 shows estimates of the Escort and the MV-22 transitioning. The plots are from a single degree of freedom differential equation to show acceleration through the transition process. Figure 6 shows the flight control system output commands sent to the Escort's tilt actuation systems.

For the point on the sea level flight envelope chosen for assessing transition: 60kn in helicopter mode to 115kn in aeroplane mode, it is concluded that stall margins for the wings and blades were comparable with those assessed by the author for the MV-22 performing a similar transition.

The transition process for the centre-line tilt rotor depends on managing asymmetric torques and forces that arise so that the aircraft has acceptable handling qualities throughout. A considerable effort will be required to capture and de-risk these issues.

Transition: Aerodynamics

During transition one rotor sustains flight allowing the other to make its transition. To achieve a successful transition, it is important that the transitioning rotor produces zero net thrust: if there is thrust, one or both of its resolved components is always in the wrong direction. Referring to Fig. 6 for transition of the LH rotor it can be seen that the sustaining rotor is the RH rotor which is still operating in a helicopter mode. Then, while the RH rotor is transitioning, it is the LH rotor that is sustaining flight by operating as a pusher prop.

So, to visualise the aerodynamics of the transition process, it is helpful to treat the transition of the first rotor separately from the transition of the second, though of course the one continues straight from the other. Further, assume as shown in Fig. 6 that the first rotor to transition is the LH.

Transition of LH rotor:

From Fig. 6 it can be seen that for the first few seconds, both rotors are tilted forward to accelerate the aircraft. At five seconds the transition of the LH rotor starts, leaving the RH rotor as the sustaining rotor and its wake affecting the LH rotor throughout the transition.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

At (a) LH at 80º tilt. Airflow enters the LH rotor disk from above the tip path plane (TPP) as in a helicopter in level cruise, and the airflow is still merged with RH. Reduction in LH collective has started and hence rotor torques no longer balance. The unbalanced torque resolves into a major component, yaw, and a smaller component, pitch. Cyclic easily balances the pitch component but not the yaw component so the aeroplane control surfaces must be gradually brought in to help.

At (b), 100º tilt. LH collective pitch has been reduced to give zero lift, and the aeroplane control surfaces now have full responsibility for torque balance. Note: the cyclic of both rotors still have full authority even as vector directions change. Where the LH rotor is still overlapped with the RH the inflow will be from above the TPP, elsewhere the inflow should be from below.

At (c), 145º tilt. Airflow, including wash from the RH rotor, enters the LH rotor from below, analogous to a helicopter in a steep 45º auto-rotational descent, except that the rotor does not need to extract energy to maintain rpm, and the collective is set for zero net thrust. The wash and turbulence from the RH rotor may cover over two thirds of the LH rotor.

As (d), 180º tilt. Approaching (d), with collective still being adjusted for zero thrust, it can be regarded as a helicopter in steep descent or as a pusher propeller on the border line between braking and propulsion. Once at (d) collective is taken further negative to produce thrust and is ready to take over from the RH for sustaining aircraft flight. The wash and turbulence from the RH rotor is expected to reduce to cover a third of the LH rotor.

Throughout the process (a), (b), (c), (d) the LH rotor will still require power for profile losses and use of cyclic pitch. Torque from the RH rotor will still need to be balanced, principally by the aeroplane control surfaces and possibly by use of LH rotor cyclic.

Transition of RH rotor:

The transition of the RH rotor can be visualised in a similar vein although the situation is different: the LH rotor is now sustaining the aircraft's flight from its 180º tilt position with reverse collective acting as a pusher prop.

At (e), RH rotor at 68º tilt. The LH rotor has already transitioned so the RH starts from working in cleaner air, no turbulence or wash from the other rotor. Its transition should be smoother in operation. Of course in the last half of its transition it is progressively overlapping and merging its aerodynamics with the LH.

At (f), RH rotor at 125º tilt. The inflow is from beneath the TPP and starting to merge with the LH rotor.

At (g), RH rotor at 180º tilt. The RH rotor can now reverse its pitch to share sustaining flight with the LH which now eases off collective to achieve equality of thrust and torque.

Cancelling the unbalanced torque from powering the rotors is easier during the RH transition. This is because nearly all power goes to the sustaining rotor which is at lower power because of the good L/D in aeroplane mode, and at 180º tilt the unbalanced torque resolves into a roll and pitch components, easily managed by the aeroplane control surfaces.

Transition: Meshing and tilting

The meshing arrangement is straight forward. It relies on the rotors being canted, 11° for Escort, and on a common cross-shaft driving both rotors' gear boxes to synchronise the meshing. It is mesmerising watching the 10kg model's rotors on bench test at low rpm to see the individual blades meshing for all possible tilt combinations: then as the rpm is increased and the rotors blur to disks, it becomes easier to focus on them as simply rotors that overlap.

The animated 3D math model used to investigate this approach allows the number of blades, the gearing ratio between the rotors and cross-shaft, the angle of cant and the relative dimensions

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

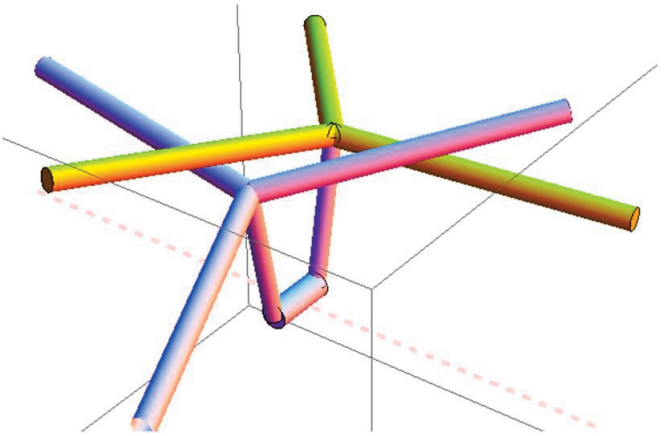


Figure 8. Snapshot from 3D animated math model of blade meshing for the Escort. Rotors canted 11° to the XZ plane and tilted to 90° vertical. Axis of tilt offset vertically towards the rotor hubs.

and geometry to be changed. Figure 8 shows blade meshing for a three-bladed rotor as assumed for the Escort.

The need for collective pitch reversal means that the range of the swash-plate actuators, say –10° to 20° for a forward tilting proprotor is probably doubled to –40° to 20° for the Escort. Clearly this will increase the relative volume and weight of its actuation system, but is not thought to be a meshing clearance problem for Escort with its well spaced hubs, see Fig. 8, at the assumed 11° angle of cant.

Figure 8 is based on a very simplified analysis, it makes no attempt to model tolerances, nor the dynamic details of transmission, airframe, hub and blading, nor the powerful interaction with the aerodynamics of the rotor and the rest of the airframe. Again, a considerable effort will be required to capture and de-risk these issues.

To match the MV-22 transition times the Escort, because of its one-at-a-time procedure, needs to tilt the proprotors at twice the speed of the MV-22. As a bench mark, a transition system capable of tilting the MV-22 proprotors at 8°/sec should be capable of easily tilting the Escort's at 16°/sec.

This actuation system is a major secondary flight control element, an integral part of the dynamics and structure of the aircraft, and so demands further study of its implementation, in particular on how it integrates into the complete aircraft, and de-risking of the design approach that emerges.

3.5 Discussion of enabling technologies

More than any other enabling technology it is clear that the Escort depends on a transition process that is novel and complex, and therefore this novelty needs to be de-risked, to investigate how it can be integrated into a complete aircraft, how to operate it in flight and how a flight test programme can be planned.

As a first step it was decided to build a 10kg model and to flight test it to explore its helicopter, fixed wing and transition performance.

That seems a sufficient hurdle for the present, but means that other enabling technologies remain to be addressed, to establish whether solutions already exist, or need to be developed and proven.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Every parameter used in the equations above is a pointer to relevant technology, and the list created would still leave out many issues.

Noise, vibration, whirl-flutter, icing, stealth, ground resonance, auto-rotation, vortex-ring state, safe handling within realistic operational constraints, weapons and counter-measures plumes and debris interaction, deck and ground handling and storage, maintenance and life-cycle costs, are some of the issues that a full project will have to solve.

Certification of the FCS software with its complete hardware system is probably the largest and most expensive design challenge for any fly-by-wire aircraft project. So where a certificated legacy FCS is available, the highest priority should be to proceed down a minimum modification route, the route that gives least certification cost.

On the very positive side, the tools and technologies that have been created and support the XV-15, V-22, AW-609, X-2 and X-3 and other rotorcraft projects, offer a comprehensive background to encourage development of the Escort into a fine aircraft.

4.0 INVESTIGATING TRANSITION WITH A 10KG MODEL

4.1 Four-stage flight test plan

The transition concept is high risk because of the novel aerodynamics and mechanics of meshing the rotors, and the asymmetric nature of the forces and torques during the one-at-a-time tilting, and the inefficiencies of proprotors with untwisted blades. It was therefore decided to build a 10kg model to investigate transition in flight. For project economy, it was important to stay within the radio control model community: obviously for proven components and operating practices, but most importantly to access the knowledge and the abilities of their experienced test pilots[20].

The 10kg model will not be a guide as to the full scale proprotors' efficiencies, as blade Reynolds are expected to be only 5% of the full scale machine; but it can provide practical lessons in implementing a control strategy, and a safe plan to flight testing that strategy. Four test stages are planned,

- Hover rig
- Helicopter mode
- Aeroplane mode
- Transition: (a) fixed points (b) full transitions

and each stage is designed to help de-risk the next.

The purpose of the hover rig is to flight test the meshing and tilting mechanisms, the basic flight control system, the rotors and powerplant in flight. The hover rig is basically a tailless helicopter with limited tilting but with full flight capability.

After completing its flight tests, the hover rig has had a temporary structure added that acts both as a fixed undercarriage and allows wings and other fuselage items to be attached to complete the 10kg model. Now the flight tests can proceed to investigate rotor and wing interactions in the helicopter mode.

Once the helicopter mode tests have been completed then the temporary undercarriage comes into its own to enable conventional runway take-off and landing, CTOL in the aeroplane mode.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Without it, take-off and landing would be complicated at best. Now the aeroplane mode flight envelope can be explored and the overlap with the helicopter mode flight envelope assessed.

By then the 10kg will be complete: the helicopter and aeroplane modes will be well practiced, including the flight control and sensors, so transition testing can proceed. To further de-risk the transition flight testing, this will be taken in two phases: fixed point transition and full transition.

The fixed point tests use CTOL to allow discrete parts of the transition process to be explored at minimum risk. A suitable starting point is (g) on Fig. 6 where both rotors are at 180º tilt and are sharing thrust equally: the ideal configuration for CTOL. Next a valid task at (g), directly relevant to transition handling and performance, is to set the RH rotor at zero thrust and flight test CTOL and flight handling with just the LH rotor sustaining flight. A further step would be to tilt the RH rotor a little, to 170º say, and repeat the CTOL flight test. So increment by increment, the transition corridor can be explored at fixed tilt combinations.

Once confidence has been achieved in the model's fixed transition handling qualities then varying tilt in flight can be explored and expanded to proving its full transition capability.

4.2 Method and limitations

The flight control system is single string with safety response fail-freeze except for the motor control which is fail-shutdown. The flight control components are standard off-the-shelf hobby radio control helicopter components. The pilot's transmitter has useful programmability, the on-board units have only basic adjustments. Data from each test is confined to the pilot's comments supported by video. There is no telemetry so there is no means of validating theoretical models of the models aerodynamic and mechanical behaviour.

All testing begins without stability augmentation, so that the test pilot can assess the unvarnished behaviour of the model. Rate gyro gain is then brought in as appropriate to reduce pilot workload, and to allow a wider focus on flight and handling characteristics.

The first purpose is to show that the centre-line tiltrotor approach, at least in model form, can achieve acceptable transition between helicopter and fixed wing modes and has a useful flight envelope in that context. It is accepted that the model operates at lower speeds and 5% of the Reynolds numbers of Escort.

A further purpose is to show a viable and safe flight test plan that can be the bench mark for planning testing and certification of generic centre-line tiltrotor configurations of this type.

Accepting these limitations, the method should be well suited to its purpose and resources.

4.3 Stage 1: Hover rig flight results (Completed Jan 2011)

All the elements of the 10kg model needed for helicopter mode testing were built and commissioned in a skeletal airframe, incorporating lessons from flight testing a 2·5kg model, namely the use of full cyclic control rather than a weight shift strategy for pitch and roll plus differential collective for yaw. Figure 9 is from the first flight of the hover rig version of the 10kg model.

Milestones achieved with the hover rig are:

- Bench demo of complete one-at-a-time transition/meshing tilt sequence
- Rotor diameter increased to improve control authority
- Symmetrical tilting in hover from 70° to 110°, TPP staying horizontal
- Flight performance and handling assessed as suitable to go to Stage 2.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press



Figure 9. First flight of hover rig model.



Figure 10. Left to right: nose down to accelerate away from hover, climbing banking turn, starting a swooping run, nose up to brake to hover, finishing with two-point vertical landing.

4.4 Stage 2: helicopter mode flight results (ongoing)

The model used for Stage 2 is the hover rig plus a temporary, long-legged fixed undercarriage that is capable of a) supporting the addition of wing and other airframe structures and b) allowing conventional take-off and landing as needed for Stages 3 and 4. Figure 10 shows it in flight with NACA 4424 wings.

Milestones achieved to date at Stage 2 are:

- Ground resonance issues resolved
- Flight test with temporary undercarriage, no wings

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

- Varying wing angle in downwash and forward flight investigated
- Acceptable to good flight and handling achieved with NACA 4424 aerofoil wings, with and without stabilisation (only used on yaw)

Remaining tasks before suitable to go to Stage 3

- Upgrade tilt actuators and wing positioning
- Test rolling take-off and landing in helicopter mode

5.0 SUMMARY

The concept of a centre-line tiltrotor Escort for the MV-22 Osprey has been described and the key design parameters assessed for the task of escorting the MV-22 on a land assault mission.

Reviewing the enabling technologies that are needed, the principal challenge was seen to be the transition process and therefore a four-stage flight test programme has been started using a 10kg model. The test plan is outlined and the results for Stage 1 and to part way through Stage 2 are reported.

Work on completing Stage 2 and preparation for Stages 3 and 4 is continuing.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the friendship and stimulation of colleagues and contacts during my career at Lucas Aerospace, now Goodrich Corp, and since then the support and encouragement of colleagues, friends and family.

Special thanks are due to Paul Heckles of the Paul Heckles School of Flying (PHSF) for his exceptional and essential skills as test pilot in flying the 2·5kg and 10kg models at the PHSF flying field.

Also thanks are due to the University of Liverpool, Gareth D Padfield FREng Emeritus Professor of Aerospace Engineering, Dr Mark D White, Flight Simulation Laboratory Manager, for the morale boost they gave to this project by persuading Ross Willington for his final year project, to assess the helicopter mode of the centre-line tiltrotor concept by modifying their XV-15 simulation suite, and to Ross for his excellent and thoughtful work.

REFERENCES

1. WERNICKE, K.G. Mission potential of derivatives of the XV-15 tilt rotor aircraft, 1981, AGARD paper 19, April 6-9, 1981, Paris.
2. JOHNSON W., BENTON H.L. and BOWLES J.V. Calculated performance, stability and maneuverability of high-speed tilting-prop-rotor aircraft, 1986, NASA Technical Memorandum 88349.
3. TRASK, J.T. The Special Osprey: Impact on Special Operations Doctrine, June 1996, Thesis presented to School of Advanced Airpower Studies.
4. WHITTLE, R. Marines want companion for Osprey — A tilt-rotor gunship could be boon for Bell Helicopter, *Dallas Morning News*, 5 July 2004.
5. NASA photo, http://www.dfrc.nasa.gov/ gallery/photo/XV-15/Medium/ECN-13840.jpg
6. MAISEL, M.D., GIULIANETTI, D.J. and DUGAN, D.C. *The History of the XV-15 Tilt Rotor Research Aircraft: from Concept to Flight*, Figs 74, A-12, NASA SP-2000-4517.
7. MCVEIGH, M.A., LIU, J., O'TOOLE, S.J. and WOODS, S. V-22 Osprey aerodynamic development — a

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

progress review, 1996, Paper 2225, 22nd European Rotorcraft Forum, September 1996, Brighton, UK,
8. LEISHMAN, J.G. and ROSEN, K.M. Challenges in the aerodynamic optimization of high-efficiency proprotors, *J American Helicopter Soc*, 2011, **56**, (1), pp 012004-1/21.
9. BURRAGE, R.G. Studies of a gunship escort concept for the MV-22, 2010, International Powered Lift Conference, October 2010, Philadelphia, PA, USA.
10. ANDERSON, J.D. *Aircraft Performance and Design*, 1999, p 217, WCB/McGraw-Hill.
11. STEPNIEWSKI, W.Z. and KEYS, C.N. *Rotary-Wing Aerodynamics*, 1984, Dover, Vol I, pp 112/118 and Vol II, pp 151/155.
12. ANGLE, G., O'HARA, B., HUEBSCH, W. and SMITH, J. Experimental and computational investigation into the use of the Coanda effect on the Bell A821201 airfoil, June 2005, 2004 NASA/ONR Circulation Control Workshop, Part 2, pp 889-910.
13. FLOROS, M.W., JOHNSON, W. and SCULLY, M.P. Advanced rotor aerodynamic concepts with application to large rotorcraft, 2002, American Helicopter Society Aerodynamics, Acoustics, and Test and Evaluation Technical Specialists Meeting, 23-25 January 2002, San Francisco, CA, USA.
14. ACREE, C.W. Calculation of JVX proprotor performance and comparisons with hover and high-speed test data, 2008, AHS Specialist's Conference on Aeromechanics, 23-25 January 2008, San Francisco, CA, USA.
15. PROUTY, R.W. *Helicopter Performance, Stability, and Control*, 1986, PWS, pp 41, 52.
16. JOHNSON, W. *Helicopter Theory*, 1994, Dover.
17. QUACKENBUSH, T.R. ET AL. Tiltrotor/tiltwing performance enhancement via active on-blade flaps, 2010, 66th Annual Forum of the AHS, 11-13 May, Phoenix, AZ, USA.
18. RAYMER, D.P. *Aircraft Design: A Conceptual Approach*, 2006, AAIA Education Series, p 347.
19. LEISHMAN, J.G. *Principles of Helicopter Aerodynamics*, 1st edition, 2000, Cambridge Aerospace Series.
20. HECKLES, P. PH School of flying, http://www.paulhecklesrc.co.uk
21. WILLINGTON, R. Flight Dynamics Advantages of the Centre-Line Tilt-Rotor Configuration, Spring 2012, Final Year Project Paper, Liverpool University.

APPENDIX A: ESCORT'S EMPTY WEIGHT

To estimate the Escort's empty weight the equations of Table A1 have been used, based on an example weight analysis of Ref. 15, and are restricted to just those items needed to change the AH-1Z into a centre-line tiltrotor escort gunship.

The equations are used first to estimate the weight of what must be deleted from the AH-1Z,

Table A1
Weight equations based on Ref. 15, weight in lb
(See Table A2 for definition of parameters)

Blading, per rotor	$\boldsymbol{Wb = 0{\cdot}026\, b^{0{\cdot}66}\, c\, R^{1{\cdot}3}\, \Omega R^{0{\cdot}67}}$
Hub/hinge/fold weight, W_{hub}	$0{\cdot}0037 b^{0{\cdot}28}\, R^{1{\cdot}5}\, \Omega R^{0{\cdot}43}\, (0{\cdot}67\, Wb + (\mathrm{g\ J}/R^2))^{0{\cdot}55}$
Drive system	$13{\cdot}6\, DS_{rating}{}^{{\cdot}82}\, (\mathrm{Npt}/1{,}000)^{0{\cdot}037}\, \mathrm{GBXm}^{0{\cdot}066}/\Omega \mathrm{m}^{0{\cdot}64}$
Nacelle	$0{\cdot}041\, W_{eng}{}^{1{\cdot}1}\, N_{eng}{}^{0{\cdot}24} + 0{\cdot}33\, Swetnac^{1{\cdot}3}$
Horizontal stabiliser	$0{\cdot}72\, Ahz^{1{\cdot}2}\, ARhz^{0{\cdot}32}$
Fin for tailrotor	$1{\cdot}05\, Av^{0{\cdot}94}\, ARv^{0{\cdot}53}\, \mathrm{GBXt}^{0{\cdot}71}$
Fin with no tailrotor	$0{\cdot}72\, Av^{1{\cdot}2}\, ARv^{0{\cdot}32}$
Wing	$1{\cdot}05\, Aw^{0{\cdot}94}\, ARw^{0{\cdot}53}$
Landing gear, × 1·1 if retractable	$40(\mathrm{MTOW}/1{,}000)^{0{\cdot}67}\, \mathrm{Nlg}^{0{\cdot}54}$
Tilt actuation, N_{tilt} is the number of tilt actuators	$1{\cdot}1\ 40(\mathrm{MTOW}/1{,}000)^{0{\cdot}67}\, N_{tilt}{}^{0{\cdot}54}$
Fuel tanks and system	$0{\cdot}1\, W_{fuel}{}^{0{\cdot}77}\, N_{tanks}{}^{0{\cdot}59}$

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Table A2

	AH-1Z**	Escort
MTOW	18,500	19,500
Engine weight, W_{eng},	458	971
Number of engines, N_{eng}	2	1
Nacelle wetted surface, *Swetnac*	35	70
Engine output shaft rpm, Npt	20,900	15,000
Drive system rating, DS_{rating}, hp	3,380	6,150
Main drive system number of gearboxes, GBXm	3·5	3·5
Tail rotor rating, TR_{rating}, hp	676	0
Tail, number of gearboxes, GBXt	2	0
Main rotor *R*, tipspeed Ω*R* and Ωm = Ω*R*/*R* radians/sec	24, 746, 31	12, 790, 65·83
Tail rotor Ω*t*, radians/sec.	153	0
Main rotor blade chord, *c*, and number of blades, *b*	2·08, 4	2·0, 3
Hub/hinge/fold weight, W_{hub}	438	77·7
Rotor polar inertia, $J = (3\ Wb + 2\ W_{hub})R^2/(9\ g)$, slug ft^2	5,955	431
Wing area and aspect ratio, *Aw*, *ARw*	58, 4·6	220·8, 3·7
Horizontal stabiliser, *Ahz*, *ARhz*	25, 4	19, 1·5
Fin, vertical stabiliser, *Av*, *ARv*	12, 3	35, 2
Landing gear, number of legs, Nlg	2	2·5
Fuel capacity, W_{fuel} lb	2,858	3,000
Number of fuel tanks, N_{tanks}	4	4

** *Author's estimates not validated by manufacturers*

Parameter values used in Tables A1 above, and A3, A4 below. Units lb, ft, ft^2 unless declared otherwise. Table A3 assumes an AH-1Z empty weight of 12,300lb and, having applied the equations, estimates the weight of all that does not change at 8,241lb, the legacy for the Escort

Table A3
AH-1Z** estimate of legacy available

	lb	% MTOW
Blading	707	3·8
Hub/hinge/fold weight, W_{hub}	438	2·4
Drive system	1,154	6·2
Engine installation	916	5·0
Nacelles	149	0·8
Horizontal stabiliser	53	0·3
Vertical fin	32	0·2
Wing	94	0·5
Landing gear	411	2·2
Tilt actuation	0	0
Fuel tanks and system	104	0·6
Legacy for Escort	8,242	44·6
AH-1Z empty weight	12,300	66·5

** *Author's estimates not validated by manufacturers*

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

Table A4
Estimate of Escort empty weight

	lb	% MTOW
Legacy from AH-1Z**	8,242	42·3
Blading	475	2·4
Hub/hinge/fold weight, W_{hub}	155	0·8
Drive system	1,432	7·3
Engine installation	971	5·0
Nacelle	162	0·8
Horizontal stabiliser	56	0·3
Fins	128	0·7
Wing	338	1·7
Tilt actuation	468	2·4
Landing gear	528	2·7
Fuel tanks and system	108	0·6
Design allowance	237	1·2
Escort empty weight	13,300	68·2

** *Author's estimates not validated by manufacturers*

and secondly to estimate the weight of the items to change it into the Escort.

Thirdly they are used to show the sensitivity of the Escort's empty weight to changes in rotor radius R, and drive system power rating, HP_{max}.

Table A4 starts with the 8,241lb legacy from the AH-1Z and uses the equations to estimate the weight of new items for the Escort and hence its empty weight at 13,300lb, with a MTOW of 19,500lb.

Combining the equations of Table A1 and linearising about the design point represented by Table 4, gives:

$$W_{empty} = k_0 + k_1 R + \mathrm{k}_2 \ HP_{max}$$

where $k_0 = 10{,}233{\cdot}1$, $k_1 = 158{\cdot}2$, $k_2 = 0{\cdot}19$

APPENDIX B: APPROACH TO SENSITIVITY ANALYSIS

The baseline land assault mission of Table 3 of the Escort provides a suitable performance criterion: the endurance margin available for a diversion.

So, sensitivity is expressed here as the extra minutes of diversion in cruise obtained from improving a design parameter by 1%. To estimate the minutes of cruise time available for a diversion, Equations (1-4) and Table 3 which applies Equation (5) to each segment of the Escort's mission have been used to create the functions '$diversion_t$ [,]' and '$design_{TO}$[, , ,]'.

$$diversion_t [\ ,\ ]$$

The first five rows of Table 3 define the fuel available for diversion, so these have been compacted

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press

into a single function called '$diversion_t$ [TO_{fuel}, EEv]' whose inputs are TO_{fuel} and EEv and whose outputs are the diversion time and, as a cross-check, an update of the complete Table 3.

$$design_{TO}[\ ,\ ,\ ]$$

To provide the needed estimates of TO_{fuel} and EEv, the Equations (1-4) have been combined to form the function '$design_{TO}$[ ]' which accepts inputs

- HP_{max}, the drive system rating
- bl % of rotor lift blocked by fuselage/wings, etc at take-off
- η, efficiency of the rotors as propellors in cruise
- L/D, the aircraft lift to drag ration in cruise

and outputs TO_{fuel} and EEv.

These are the results. Improving the following parameters yields extra diversion time

- Rotor blockage reduced from 4·8% to 3·8% yields 13·4 minutes extra
- 1% reduction of empty weight yields 8·9 minutes extra
- 1% increase in FM yields 8·5 minutes extra
- 1% in rotor radius R yields 7·2 minutes extra
- 1% in hub separation (from zero) yields 2·7 minutes extra
- 1% of η, L/D, ζ, or SFC yields 1·8 minutes extra

As a generalisation, the capability to lift fuel at take-off dominates 5 to 1 over the efficiency of using that fuel over the rest of the mission.

https://doi.org/10.1017/S000192400000806X Published online by Cambridge University Press