Proposal for the 2011 AHS Request for a Multi-mission Rotorcraft: GT VADR (Variable Diameter Tilt Rotor)

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Georgia Institute of Technology

GT VADR

Multi-Mission Rotorcraft Design

PRIMARY CONSIDERATIONS

• Airspeed range target 192 – 230 kts
• Hover Power required for 6k95
• Operation radius of 250 nm
• 4000 lb payload

SECONDARY CONSIDERATIONS

• ICAO Level 4 noise
• Reconfigurable cabin
• IR suppression considered
• Non-recurring/operational hourly cost
• Op availability for 3 missions/week

http://vtol.org/awards/sdcomp.html

CAPITALIZE ON TILT ROTOR BENEFITS

• Low risk 300 knot dash speeds
• Better Lift/Drag ratios over helicopters
• High Best range and loiter speed
• Cruise altitudes 20k ft+, self deploy

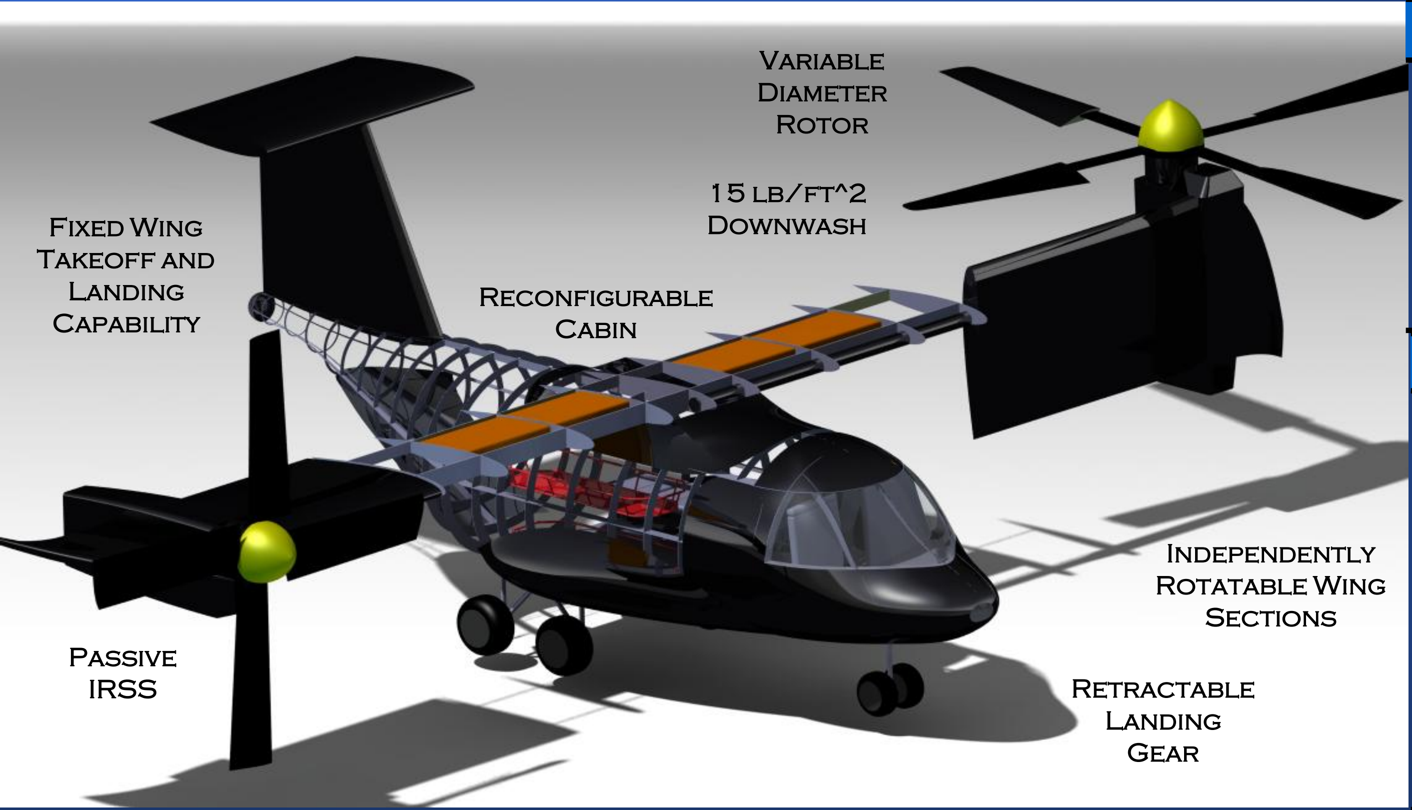
FOCUS ON ISSUES W TRADE STUDIES

• High downwash for unimproved fields
• High weight fractions
• Poor autorotation/emergency landing
• Vertical download weight penalties
• Poor yaw rates in hover

BALANCE TECH INSERTION/RISK

SENSITIVITY TO "GUARANTEED" GROWTH AND VARIATION

VADR Design Features



Critical Dimensions	
Rotor Radius, ft *(Contracted)*	13.5 *(9)*
Wingspan, ft	54.7
Tip Speed, ft/sec *(Contracted)*	650 *(405)*
Solidity	0.09

Mission 2 Parameters	
TO Gross Weight, lbs	15100
Empty Weight, lbs	8200
EW Fraction	0.54
Fuel Required, lbs	2090
MCP Available, hp	2350
SFC, lb/hp-hr	0.34
Rotor Diameter, ft	27
Max Speed, knots	300

Requirements Summary

Focused preliminary design to satisfy all AHS specified requirements

Identified and incorporated implicit AHS design requirements

Incorporated basic civil tilt rotor requirements using the BA609 certification as a guide

Incorporated some expected military requirements; loosely coupled to new JMR program

Integrated requirement analysis into real time design environment

Requirement	Type	Status	Comments
Mission 1 - Search and Rescue	AHS		Incorporated into Design
Mission 2 – Insertion	AHS		Incorporated into Design
Mission 3 - Resupply	AHS		Incorporated into Design
Velocity - 192 - 270 kts	AHS		300 kts at 6k95
4000 lb Payload	AHS		4000 lb payload design point
250 nautical mile radius	AHS		Incorporated into Design
4 crew	AHS		Incorporated into Design
6 passengers	AHS		Incorporated into Design
Reconfigurable cabin	AHS		Incorporated into Design
ICAO Level 4 Noise	AHS		WOPWOP Analysis
6k95 HOGE	AHS		Blade Element Performance Analysis
CT7-8A Rubber Engine	AHS		2300 HP per engine (optimized design)
Vertical Download	Other		15 lb/ft^2 design point
Takeoff/Landing Performance	FAR		Fixed Wing Performance, Part 25, OEI
Structures	FAR		Developed V/N diagrams for all config
Single Engine Operations	FAR		OEI (One Engine Inop) Analysis
IFR Considerations	FAR		45 min reserve added
Transition	FAR		Transition does not reduce altitude
Weight	Other		15100 Mission 2 (20k adequate, 15k desired)
Cost Considered	Other		$17 Mil per a/c, $1667/hr (Bell cost model)

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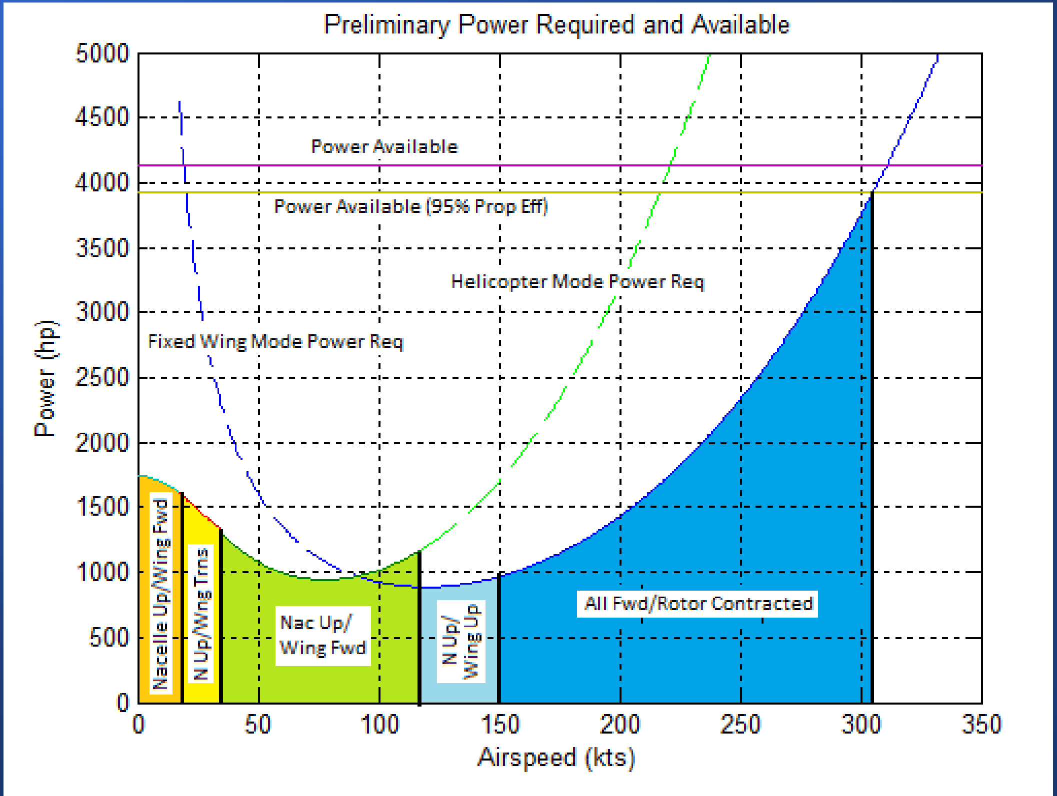
GT VADR

VADR Performance with Wing/Nacelle Scheduling

Configuration	Airspeed
W/N Up	0 - 15 kts
W Trans/N Up	15 - 30 kts
W Fwd/N Up	30 - 120 kts
W Fwd/N Fwd	120 kts
Rotor Contract	150 kts +



6k95+ Hover Capability

300 kt+ Maximum Airspeed (95% Propeller Efficiency) for "Golden Hour" in 45 min

180 kt Best Range Speed for reduced mission times

125 kt Loiter Speed

200 kt+ (estimated) helo mode forward airspeed, recommended upper transition limit at 150 kts

Substantial Power Margins for Transitions

295 kts at 20,000 ft allowing for robust mission planning

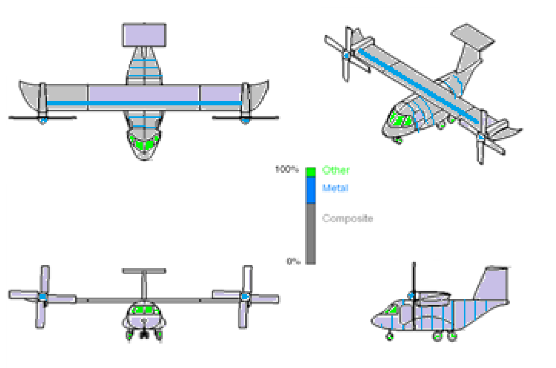
Maneuver Envelopes and Structural Details

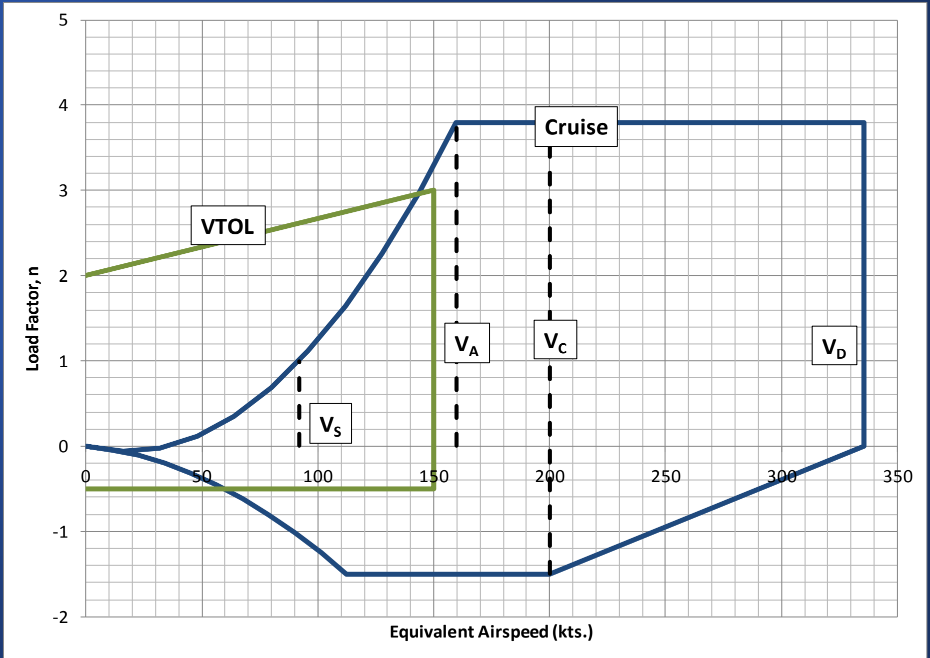
Uses mixed metal and composite structural layout to balance manufacturability, reparability and cost

Initial operational envelope consistent with power requirements

V-N diagrams developed using BA-609 certification guide for helo and fixed wing mode to include gust rejection

Integrated structural layout into CATIA model for design decisions

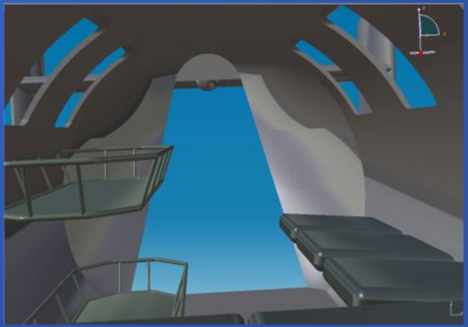




Initial Operational Envelope for Helo/Fixed Wing Mode

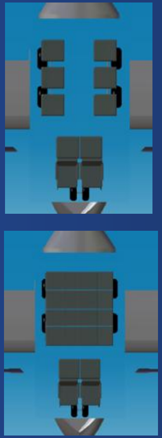
Multi-Mission Performance

Search and Rescue	Mission 1
TOGW (lbs)	12399
Mission Time (hr)	3.5
EW Fraction	0.61
Fuel Required	3034
MCP Available (hp)	1946
SFC (lb/hp-hr)	0.34
Rotor Dia. (ft)	26.6
Retracted (60%, ft)	16
Max Speed (kts)	300

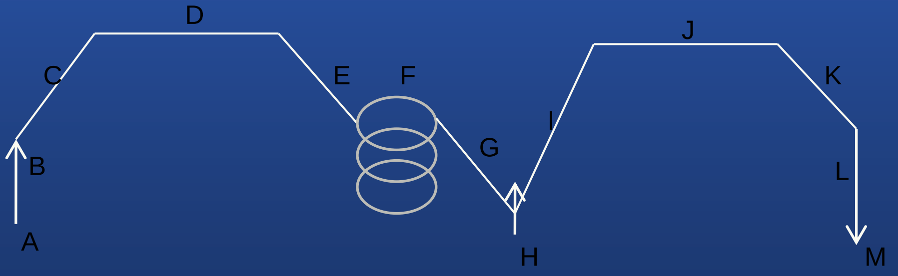


MEDEVAC Cabin Configuration

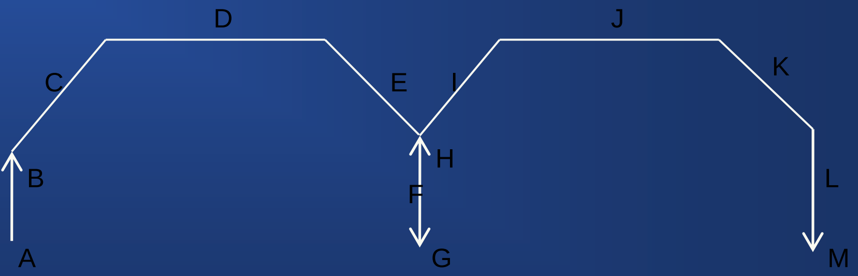
Insertion	Mission 2
TOGW (lbs)	15101
Mission Time (hr)	3.25
EW Fraction	0.54
Fuel Required	2085
MCP Available (hp)	2346
SFC (lb/hp-hr)	0.34
Rotor Dia. (ft)	26.6
Retracted (60%, ft)	16
Max Speed (kts)	300



Resupply	Mission 3
TOGW (lbs)	14956
Mission Time (hr)	3.55
EW Fraction	0.55
Fuel Required	2956
MCP Available (hp)	2325
SFC (lb/hp-hr)	0.34
Rotor Dia. (ft)	26.6
Retracted (60%, ft)	16
Max Speed (kts)	300



Search and Rescue Functional Profile



Insertion/Resupply Functional Profile

Fixed Wing Versatility and Emergency Handling

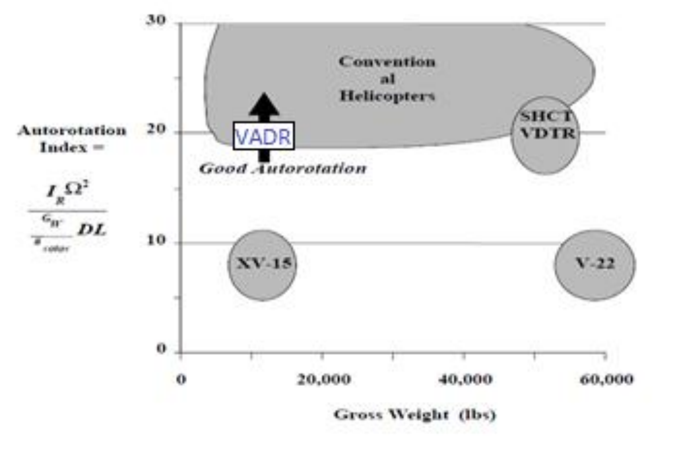
VADR brings unique fixed wing capability over all flight segments.

Fixed Wing takeoff and landing performance calculated to allow for operation at the majority of improved runways.

Engine out cases analyzed according to FAR Part 25.

Ferry analysis for self-deployment mission, assuming 4000 lb ferry fuel.

Segment	Result
Fixed Wing TO Distance (ft)	2,600
Fixed Wing Landing Distance (ft)	2,800
Fixed Wing OEI TO Distance (ft)	4,200
Ferry Range (nm)	5,200
Autorotation Index	20



"Advancing Tiltrotor State-of-the-Art with Variable Diameter Rotors" AHS Forum 48. **Evan A. Fradenburgh, David G. Matuska,.** 1992.

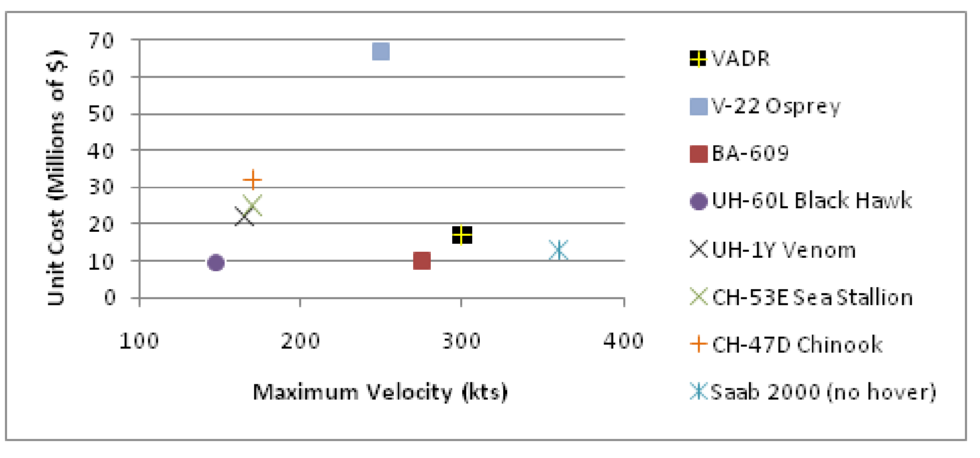
Fixed wing configuration allows for improved glide over rotorcraft.

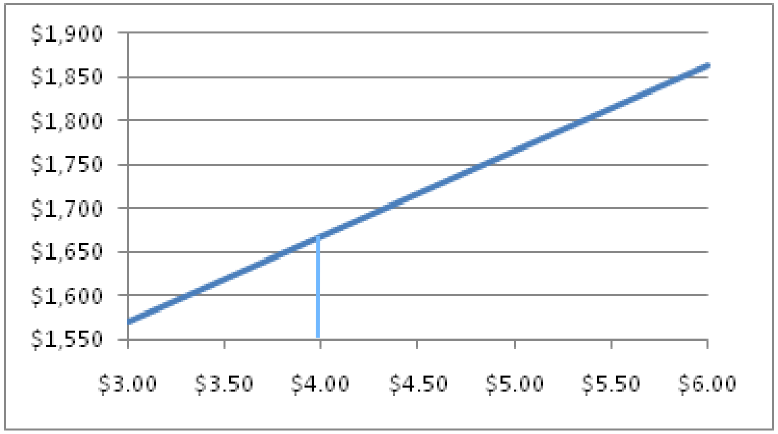
VADR blade system weight increases Autorotation Index for improved rotorcraft configuration emergency handling over current tilt rotors.

Procurement and Operational Cost

- Estimation by Bell Helicopters PC based Cost Model
- Cost model allows for increases considering technology factor:
  - VDTR – TRL 5, cost estimate +20% to rotor system
  - Active Aileron – TRL 2, cost estimate +15% for flight controls
  - Variable Wing Section – TRL 5, cost estimate +8% for wing

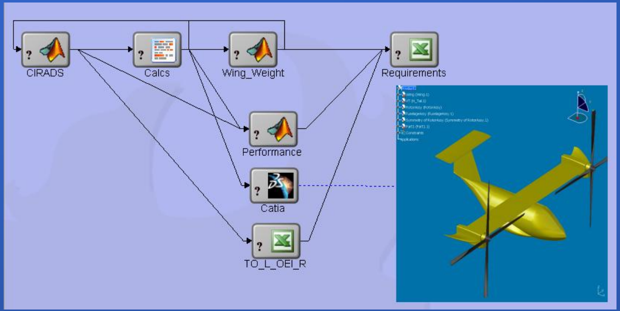
Total Development Costs	$522.8 Mil
Cost per A/C (First 100 units)	$18 Mil
Cost per A/C (After 100 units)	$17 Mil
Total Operating and Support Cost	$1667/hr



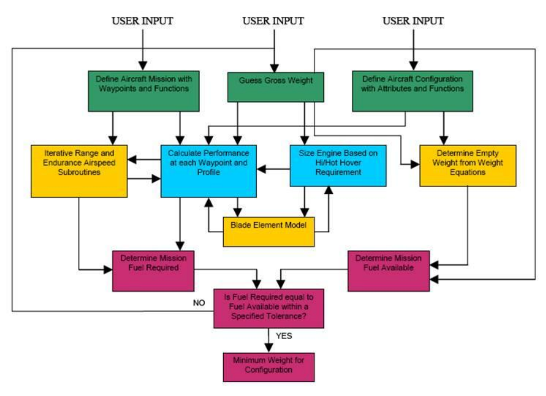


O&S Sensitivity to Fuel Cost ($/gal)

Model Center Design Environment



Model Center Environment



CIRADS Flow Diagram

Model Center environment allows for multiple analysis tools with consistent design parameters, inputs and outputs.

Tools in iterative design loop:

- CIRADS – Momentum based Georgia Tech design code
- Performance Analysis – MATLAB code for power available and required
- Fixed Wing Performance – MATLAB code for fixed wing takeoff/landing/OEI
- CATIA – Physical modeling including weight and center of gravity calc
- Structural Wing Analysis – MATLAB code originally from sizing program for JVX
- Requirements Analysis – EXCEL requirements tracking and design decisions
- Blade Element Hover – MATLAB code to verify 6k95 and support VDTR design
- Engine Sizing – MATLAB code supporting rubberized CT7 engine model

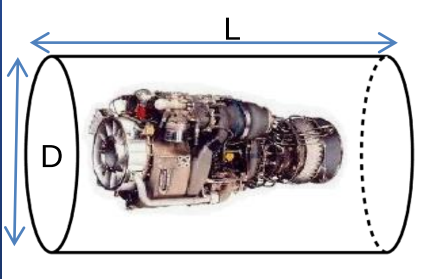
Tools feeding design (normally due to long tool analysis times):

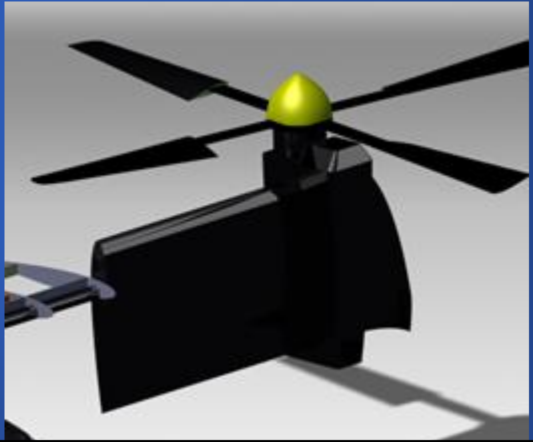
- MBDyn – Dynamics modeling tool for blade design
- Star-CCM+ - Computational fluid dynamics code
- FLIGHTLAB – S&C design tool, flight control system modeling and HQ analysis
- WOPWOP – Aircraft noise analysis tool

Conducted Design of Experiments for overall optimization

Engine and Transmission Sizing

- Required CT7-8A "Rubber" Engine
- Engine performance and sizing MATLAB code developed from AHS 2007 RFP
- Basic model in CATIA created
- Data used in FLIGHTLAB
- Basic Engine Sizing
  - Diameter = 35.3 in.
  - Length = 61.4 in.
  - Power to Weight = 5.1
- Consider technology adjustments
- Significant room for horsepower growth





Engine Parameter	Value
Engine Weight, lbs	230.1
Installed MRP, HP	2,034
MCP cruise, HP	590
SFC cruise, lb/HP*hr	0.368
Idle Power, HP	203.45

- Empirical Transmission Sizing

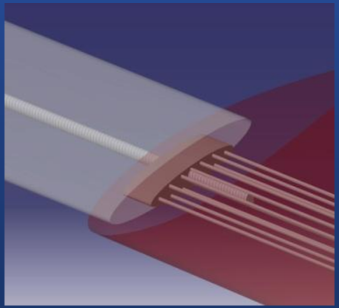
$$W_{DS} = 42.4\left(\frac{HP \cdot R}{V_T}\right)^{0.763}$$

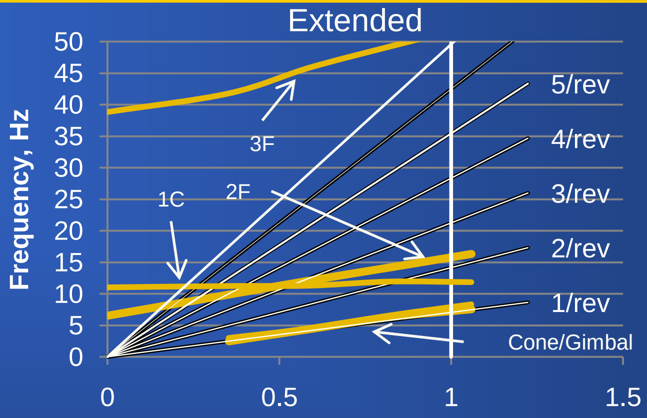
- Simplified transmission as rotor speed changes are dictated by variable diameter rotor

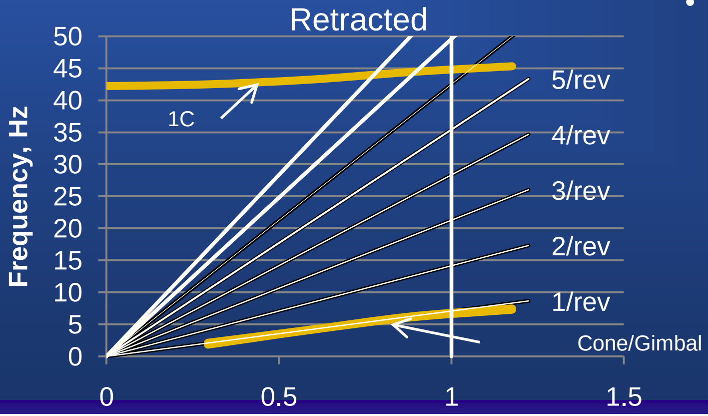
Drive Systems Initial Sizing	
HP	4000 hp
HP (contingency)	4800 hp
Rotor Diameter	27 ft
Rotor Radius	13.5 ft
Rotor Tip Speed	662 fps
Torque	3323 ft lbs
Torque Contingency	3988 ft lbs
Weight drive system	**1400 lbs**

Trade Study: Variable Transmission/VDTR

- Necessary to slow rotor tip speed in high speed forward flight
- Can be accomplished by reducing rpm in transmission or reducing radius
- Most literature on VDTR show an un-faired cutout section when the blade is extended to maximum diameter.
- Maximum radius reduction of 40%.
- Known wind tunnel tests, TRL 5





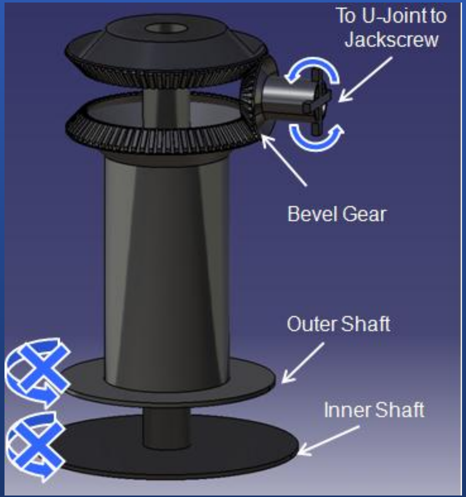


- Trade study supports movement of design rotor RPM to avoid forcing frequencies and maintain hover requirements
- Analysis incorporates CIRADS design parameters.
- Developed blade element code to analyze the stringent 6k95 hover requirement.
- Detailed retraction schedule, estimated at 120 – 150 knot transition

Fwd Flight Radius	8.16 ft
Cutout	5.34 ft
Hover RPM	425 rpm
Hover Pwr Reqd (hp)	1120 (per)

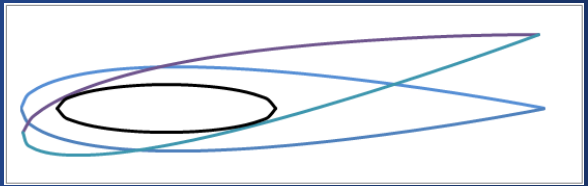
VDTR Actuation and Rotor Airfoil Design

- System spins with outer rotor shaft
- Brake the inner shaft to extend
- Brake the outer shaft to retract
- Retraction takes about 20 seconds
- Very low torque required



- Blade Properties
  - Linear twist of -20 degrees, NACA 0015 airfoil
  - Increased root structure for stability
  - Moderately stiff-in-plane [1.6p], no unfavorable mode crossings
- Gimbaled hub
  - Stiffness sized from Sikorsky recommendations
- Balance technology insertion with other low risk components

- Simple Box Beam
  - Internal/external section
  - Combined section
- Dimensioned from NACA 0015
  - Shrunk to allow aerodynamic portion to twist



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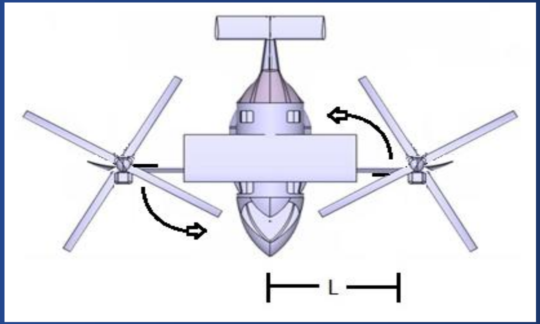
Trade Study: Vertical Download

- Present tilt-rotors typically have a vertical drag factor (rotor download on wing) equivalent to 10-15% GW, requiring more thrust for hover
- Using a tilt-wing section just below the rotor wake can reduce download to ~1%

$$e_d = \frac{S_{\exp} B}{3A_d} = \frac{15\text{ft}^2 * 0.97}{3 * 515\text{ft}^2} \approx 0.01$$

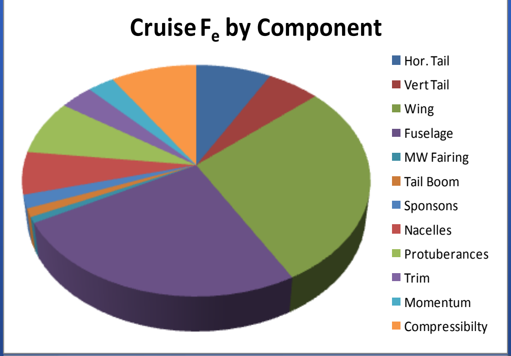
- Vertical wing sections can have a stabilizing affect on rotor control inputs
- Addition yaw moment can be generated by deploying ailerons in hover condition
- Potential susceptibility to gusts, mitigate with handling qualities simulation and flight tests
- Tilted Wing – TRL 5, Active Ailerons – TRL 2

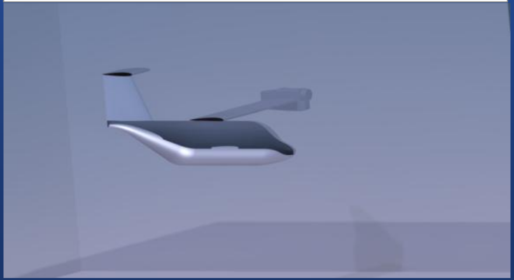


Ratio aileron/wing chord	0.2
CL (flap)	0.698
Aileron Area	16.8 ft^2
Inflow (Hover 6k95)	40 ft/s
Lift Calculated (aileron deployed 20 deg)	111.37 lbs
Distance to CG (L)	~16 ft
Additional Yaw Moment	1781 lb ft
Moment of Inertia about Vertical Axis	18100 slug*ft^2
Commanded Angular Acceleration	0.57 deg/s^2
Angular Rate after 5 seconds	7.125 deg/s

Drag Analysis

Configuration	Fe (sq ft)
Cruise (nacelle fwd)	14.2
30 deg nacelle/wing	142
Helo (nacelle/wing hp)	465



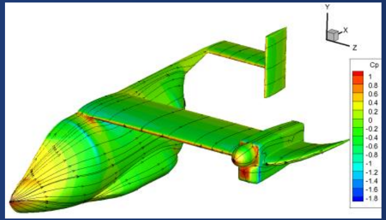


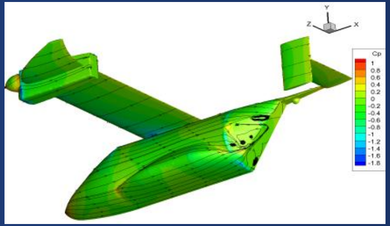
DRAG BUILDUP (Initial drag estimates were parametric)

- Manual piece-wise summation of structural components using real geometry (Lifting Surfaces and Bodies of Revolution)
- Reference Hoerner's *Fluid-Dynamic Drag* and Bell Helicopter proprietary methodologies
- For helo mode, estimates assumed nacelle and rotatable wing section together
- Used for performance analysis, then updated with follow-on CFD analysis

INITIAL CFD

- Initial CFD analysis was performed on the preliminary outer mold line using CFD++ (Metcalf Technologies)
- Half-body symmetric vehicle, unstructured mesh of 5 million elements
- Used search and rescue mission configuration with a 300 knot velocity at 20k ft
- Identified areas for improvements for future fuselage work including separation of rear fuselage, wing/fuselage joint section and engine inlet





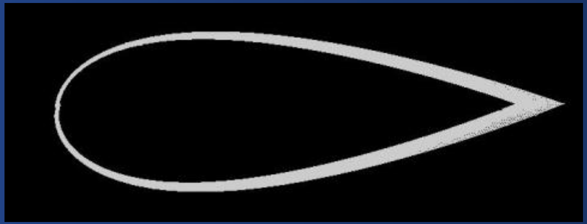
PLAN AHEAD FOR CFD

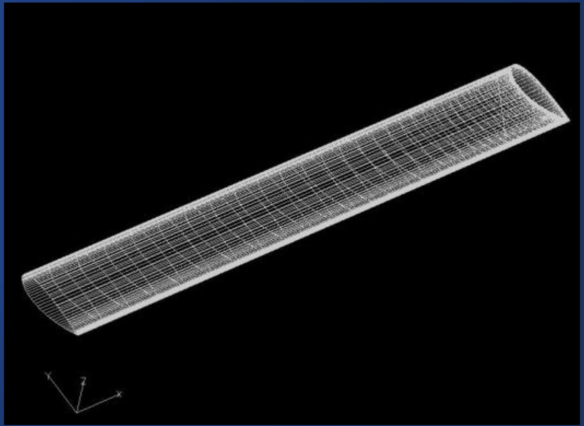
- Use mold developed from water tight CATIA model, Java macro in place
- Fuselage optimization
- Perform runs at cruise speed varying altitude and tilt wing angles
- Verify speed ranges for wing/nacelle sections for transition

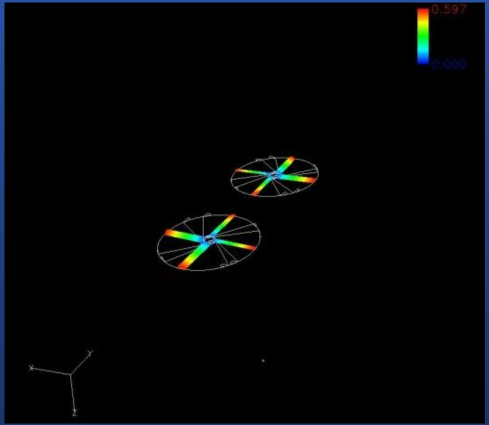
Noise Analysis

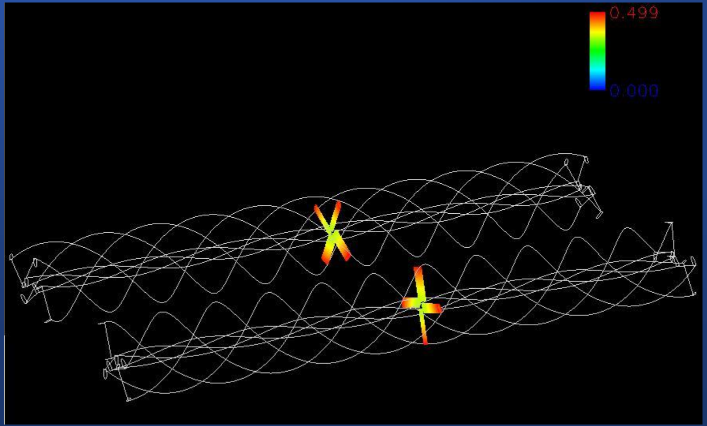
- Rotor configuration established in PSU-WOPWOP
- Hover configuration originally evaluated for microphone 60 ft away from centerline in hover but twin rotor did not produce believable results
- Evaluated the tilt rotor specific requirements from ICAO Appendix 16, Volume 1

Flight Mode	Resulting Noise Measurement (EPNdB)	Required Noise Level (EPNdB)
Takeoff	56.5	< 100
Overflight	35.7	< 99
Approach	65.0	< 101









IRSS Considerations

Infrared Suppression System

- Module 1: conceal heated exhaust duct
- Module 2: limit “lock-on” sight lines to turbine
- IR detecting missiles are readily available to hostiles around the world
- Hand-held SAMs typically lethal from 0-4000 ft
- Exhaust plume 10% contributor. Hot surfaces (e.g. metal exhaust duct) & power turbine create most significant detectable IR signature
- Tilt rotor design does not exhaust onto aircraft surfaces
- Limited threat vulnerability to taking/landing/insertion

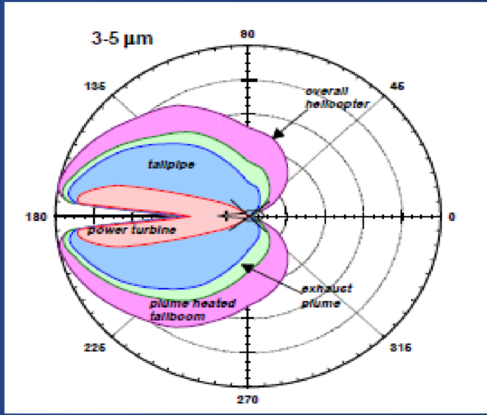


Image courtesy J. Thompson

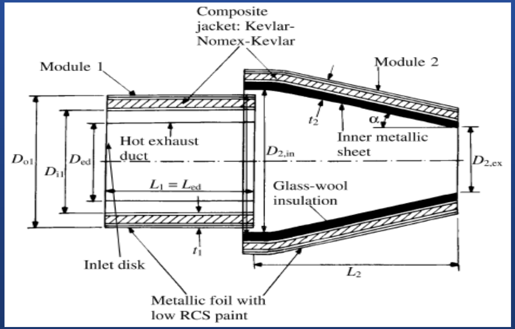


Image courtesy of Mahulikar, et. Al.

DESIGN – Address major offenders with passive control

- Incorporate low IR signature paint to reduce sunshine effects
- Module 1: Conceal heated exhaust duct
- Module 2: Limit “lock-on” sight lines to turbine
- Penalties: Minimal drag increases, 1 – 3 % loss to Power Available, 30 lb maximum added weight
- Later incorporation of additional Aircraft Survivability Equipment

Transition

ERICA concept schedules nacelle and wing section deployment independently (AIAA 2003-2015)

- Nacelle moves non-linearly to 70 deg by 50 kts; 0 deg by 150 kts
- Wing section immediately moves down with forward airspeed, linearly transitioning to full fixed wing mode by 80kts.

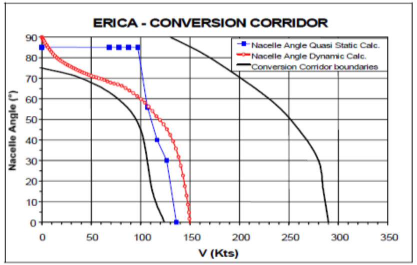


Figure 18: Conversion corridor and optimised path

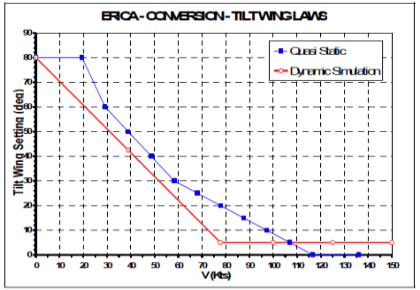
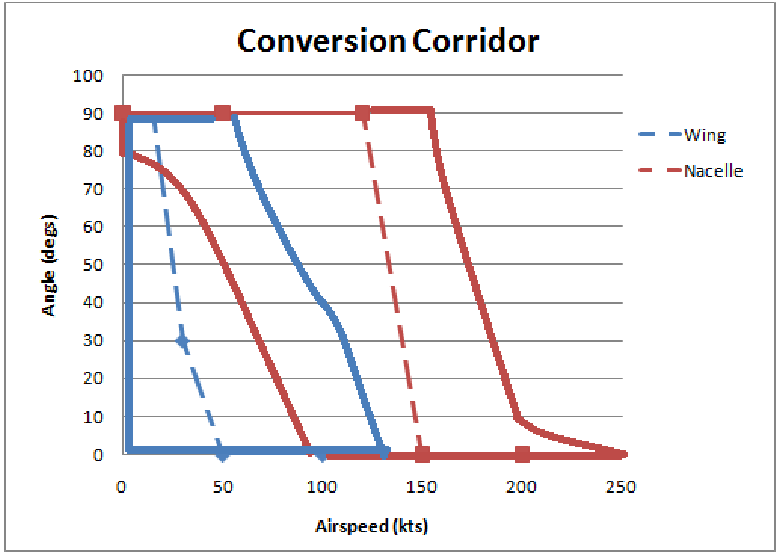


Figure 20: Tilting wing optimised angle

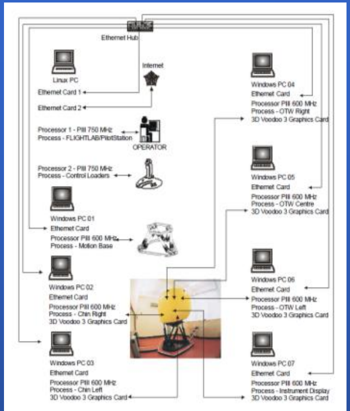


VADR Wing and Nacelle Conversion Corridor

Developed acceptable conversion corridor as part of transition study.

- Used developed power required curves to schedule wing and nacelle section movements without large power differences.
- FARs require transition to fixed wing mode without loss of altitude
- Analyze handling qualities during transition where possible

Flight Controls and Handling Qualities



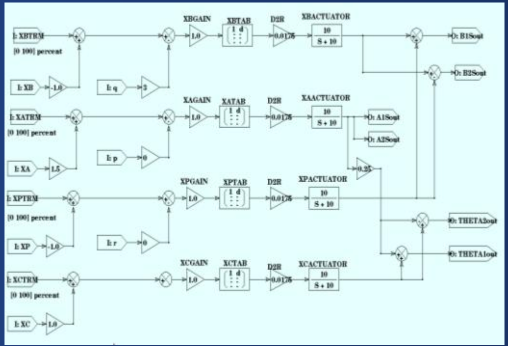
HELIFLIGHT Schematic

Flight Control System Development

- Planned Fly-By-Wire System with hover and fixed wing controls laws scheduled by airspeed and nacelle /wing angle
- Model compiles and trims in the hover condition

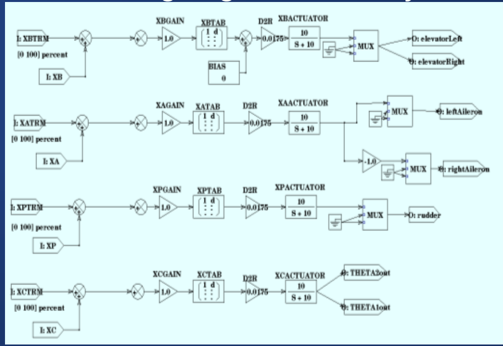
FLIGHTLAB Model Development

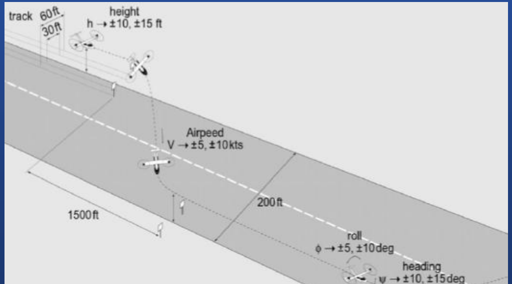
- Model compiles and trims in the hover condition
- Model allows configurable wing section and nacelle
- HQ test matrix to show design meets mission profiles including maneuvers for search and rescue operations, climbs & descents, nap of the earth and transition



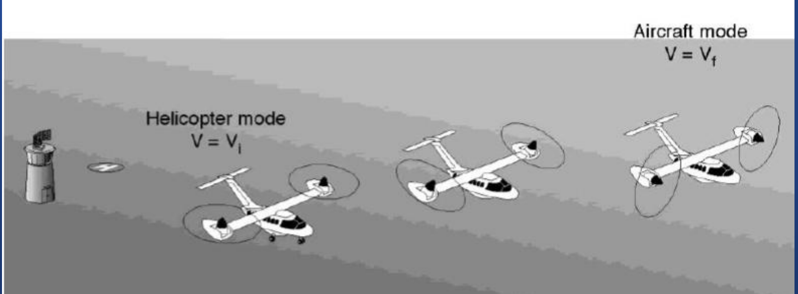
Helicopter Flight Control System

Fixed Wing Flight Control System





Roll Step MTE



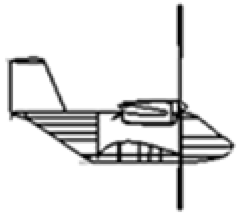
Rapid Conversion MTE

Multi-Mission Growth

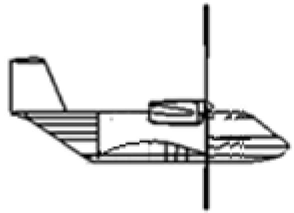
- VADR successively conducts Search and Rescue, Insertion and Resupply missions as defined by AHS requirements
- Design balances tech insertions with low risk selections, maintains margins for growth and identifies areas for further optimization
- Configuration as presented has self-deployment capability with high best range speeds and ISR capability with variable loiter speeds

Payload (lbs)	6000	8000	10000	12500	15000
GW	18513	21242	23979	27379	30779
MR Radius	14.03	15.04	15.93	17.04	18.07
Solidity	0.088	0.082	0.078	0.073	0.068
RotorBladeWt	1436	1569	1703	1854	2001
Wing Weight	1711	1596	1507	1408	1328
Max Cont Power	2986	3415	3849	4394	4948

- Current AHS requirements match closely with preliminary JMR requirements for the light category
- Design can easily be expanded to meet medium requirements with little change



VADR - Light Category



VADR - Medium Category

JMR Class	Light	Medium	Heavy
Speed	>170-300+ kts	>170-300+ kts	>170-300+ kts
Op Radius	~424 km*	~424km*	~424km*
Payload	~2k-4.5k lbs	~6k-20k lbs	~20-30k lbs
Passengers**	~4-6	~11-24	~33-44
Joint Missions	Recon ISR MEDEVAC SOF SAR Amphib Assault Attack ASW ASUW C2 Transport Security	Recon ISR MEDEVAC SOF SAR Amphib Assault Attack CSAR ASW ASUW VERTREP MCM C2 VOD Cargo/Lift Transport Security	Recon ISR SOF Amphib Assault CSAR VERTREP MCM VOD Cargo/Lift Transport