Industry Day

Mission Adaptive Rotor (MAR)

DARPA Team

Tactical Technology Office

Defense Advanced Research Projects Agency

3 March 2009

Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor Program

Industry Day Agenda

7:30 – 8:00	*Registration*	
8:00 – 8:15	Welcome	Mr. Dave Neyland, DARPA/TTO
8:15 – 9:00	Service Comments	Service Representatives
9:00 – 10:00	Mission Adaptive Rotor Program Overview	Mr. Dan Newman, DARPA/TTO
10:00 – 10:15	*Break*	
10:15 – 10:45	Mission Benefits of Active Rotor Controls	Dr. Hyeonsoo Yeo, AFDD, US Army
10:45 – 11:00	BAA Description	Mr. Chris Glista, DARPA/CMO
11:00 – 11:15	DARPA Security	Mr. Mark Dao, DARPA/SID
11:15 – 11:30	Submit Questions	
11:30 – 12:00	Technology Presentations	
12:00 – 12:30	*Working Lunch*	
12:30 – 12:50	Technology Presentations	
12:55 – 1:30	Government Response to Questions	
1:30	Adjourn General Session	
1:30 – 1:45	*Break*	
1:45 – 5:25	Industry Poster Session & Teaming Discussions	
1:45 – 5:25	Proprietary Briefings to Government / Government Caucus	
5:30 – 5:45	Closing Remarks / Look Ahead *(Optional)*	Mr. Dan Newman, DARPA/TTO

Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor Program

Industry Day Administrivia

Facility Layout

- Briefings
- Sidebars
- Poster Session
- Rest Rooms
- Emergency Exits

DARPA Team

- TTO Office Director
- DARPA CMO
- DARPA Security
- MAR PM
- Support Staff

Data Classification

- General Session:
  Government Use, UNCLASSIFIED
- Government Sidebars:
  Proprietary, up to SECRET COLLATERAL
- Industry Sidebars:
  UNCLASSIFIED, Disclosures per Industry Agreements

Badge Identifiers

- **Red Sticker:**
  Foreign National / Foreign National with US Permanent Residence Status
- **Blue Sticker:**
  Security paperwork received

Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor Program

Industry Day Objectives

1. To familiarize participants with DARPA's vision for the Mission Adaptive Rotor (MAR) Program
2. For the government to gain feedback on the feasibility of the MAR approach
3. To promote understanding of the potential BAA proposal requirements among potential offerors
4. To promote discussion of synergistic capabilities among potential program participants

Approved for Public Release – Distribution Unlimited, Case #13017

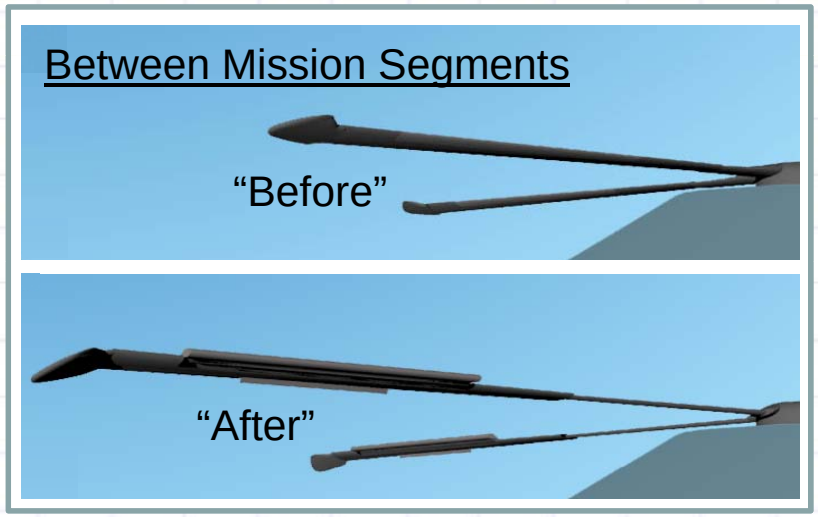
Mission Adaptive Rotor

Program Goal

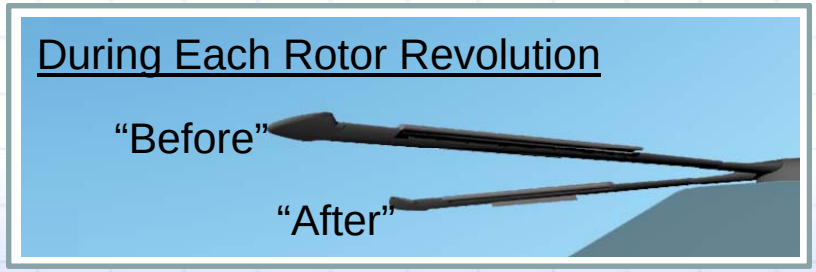
The goal of the Mission Adaptive Rotor Program is to develop "on-the-fly" morphing rotor technology, and to demonstrate the dramatic benefits possible by actively changing the rotor configuration in flight.

Dramatic improvements in rotorcraft capabilities – performance, survivability and availability – over that possible with a single, fixed-geometry rotor can be achieved by actively morphing the shape and/or properties of a rotor between disparate flight conditions

Adaptation <u>between segments of a mission</u> allows optimization of the configuration to maximize the desired attributes during each flight phase



Adaptation <u>during each rotor revolution</u> enables an optimized design for each of the dramatically different conditions experienced



Potential Adaptations / Technologies

- Variable Blade Planform
  - Diameter
  - Sweep
  - Chord
  - Tip Shape
- Variable Airfoils / Camber
  - Flap / Trim Tab
  - Slat
  - Slots / Blowing
  - Zero Mass Actuators / Flow Control
- Variable Twist
- Variable Anhedral / Dihedral
- Variable Tip Speed
  - Diameter
  - Rotational Speed / rpm
- Variable Properties
  - Modulus
  - Damping
- Control Systems & Sensing
  - Feed Forward / Feedback Control Systems
  - Vortex Sensing & Control
  - Self-Healing Adaptation
  - Swashplateless

Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor

Program Objectives

The MAR Program seeks to

1) Develop a robust system design that maximizes military utility by actively reconfiguring in flight to provide best performance during a range of missions or mission segments
2) Mature critical enabling technologies
3) Validate through simulation, ground test and flight demonstration that rotor adaptation is feasible, practical, of military value, and sufficiently mature for application to the next US military rotorcraft development effort
4) Substantiate mission capability improvements over a state-of-the-art fixed geometry rotor:
   - 30% increase in payload / 40% increase in range
   - 50% reduction in rotor acoustic detection range
   - 90% reduction in vibration
   - Improvements/no degradation in availability, speed, maneuverability, agility, shipboard compatibility, etc.
5) Demonstrate capability of high-fidelity computational analysis methods to reduce cost and compress development timeline of advanced rotors and rotorcraft

Approved for Public Release – Distribution Unlimited, Case #13017

Additional Thresholds and Objectives

Technology development must consider impacts on all key rotor / platform attributes

Other attributes be improved if possible or at a minimum, the impacts should be small and acceptable

Below recommended thresholds (minimum acceptable levels) and objectives (desired levels) are presented for important attributes other than those specific in the quantitative MAR metrics

Criteria	Threshold	Objective
Speed	Comparable to fielded systems	50 knot speed increase vs a state-of-the art fixed rotor
Marinization	Shipboard capable on large ships	Shipboard compatible with all helo-capable ships
Reliability	Comparable to fielded systems	Rotor and rotor controls not a factor at system level
Parts Count	Not more than 10% higher rotor parts count	25% reduction in rotor and rotor control parts

Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor

Technical Approach

DARPA intends to solicit, identify, develop and flight demonstrate novel adaptive rotor/proprotor technologies that offer breakthrough performance by capitalizing on reconfiguration to get outside the "passive design box", greatly expanding the solution space available

Envisioned program includes

- Solicitation seeking advanced, adaptive technologies and approaches to rotor/rotorcraft "in flight" reconfiguration
- Investments to design, develop and test an affordable, large-scale adaptive technology demonstration rotor
  - Concept Formulation and Military Utility Assessment
  - System Design, Technical Maturation / Risk Reduction
  - Large Scale System Fabrication, Integration and Ground Test
  - Large Scale Flight Experimentation
- Application of high-fidelity computational tools by industry, and correlation with large scale testing, to promote accelerated design and development of advanced rotor / rotorcraft configurations

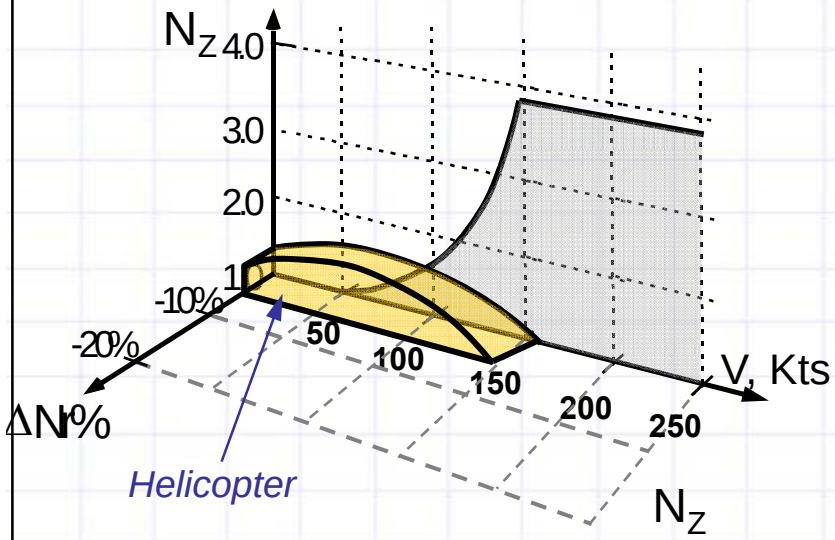
Approved for Public Release – Distribution Unlimited, Case #13017

Next Dramatic Leap in Rotor Research:

Adaptation Eliminates Constraint of Single Configuration

How is rotor design done now?

Current Rotor Compromise Between Extremes



Normal Helicopter V-N diagram

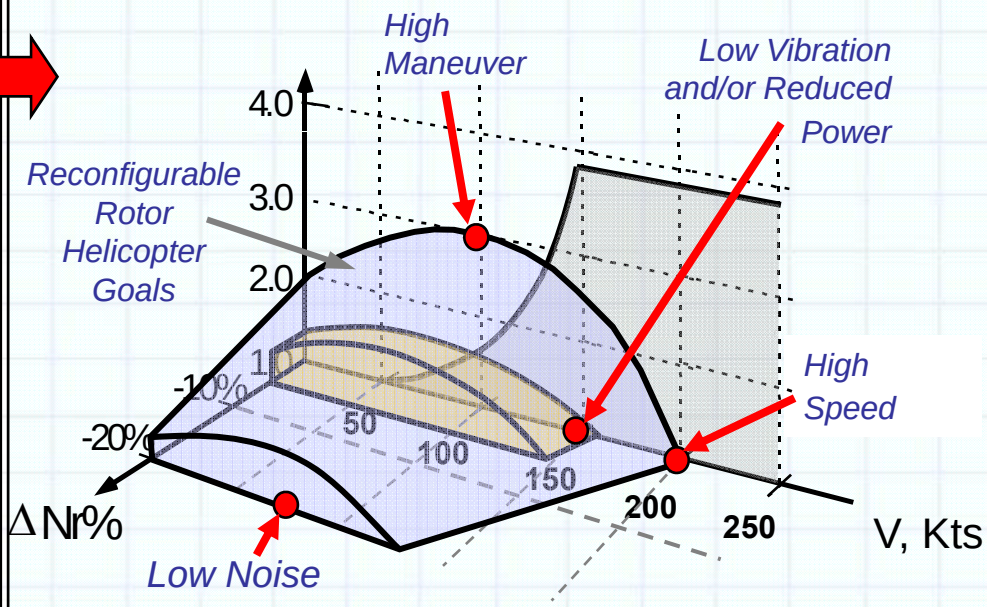
Size rotor for efficient hover

- Moderate speed
- Moderate load factor
- Costly noise reduction

Significant rotor area increase required for appreciable gains on any axis

How should rotor design be done?

- **Azimuthally controllable high lift devices enable improvement in all three axes**
- **Reconfigure devices in flight for each mode**



Adaptation Time Scales

- During 1 Revolution (Higher Harmonic Control)
- Between Mission Segments
- Between Missions

Next generation rotor can customize, not compromise

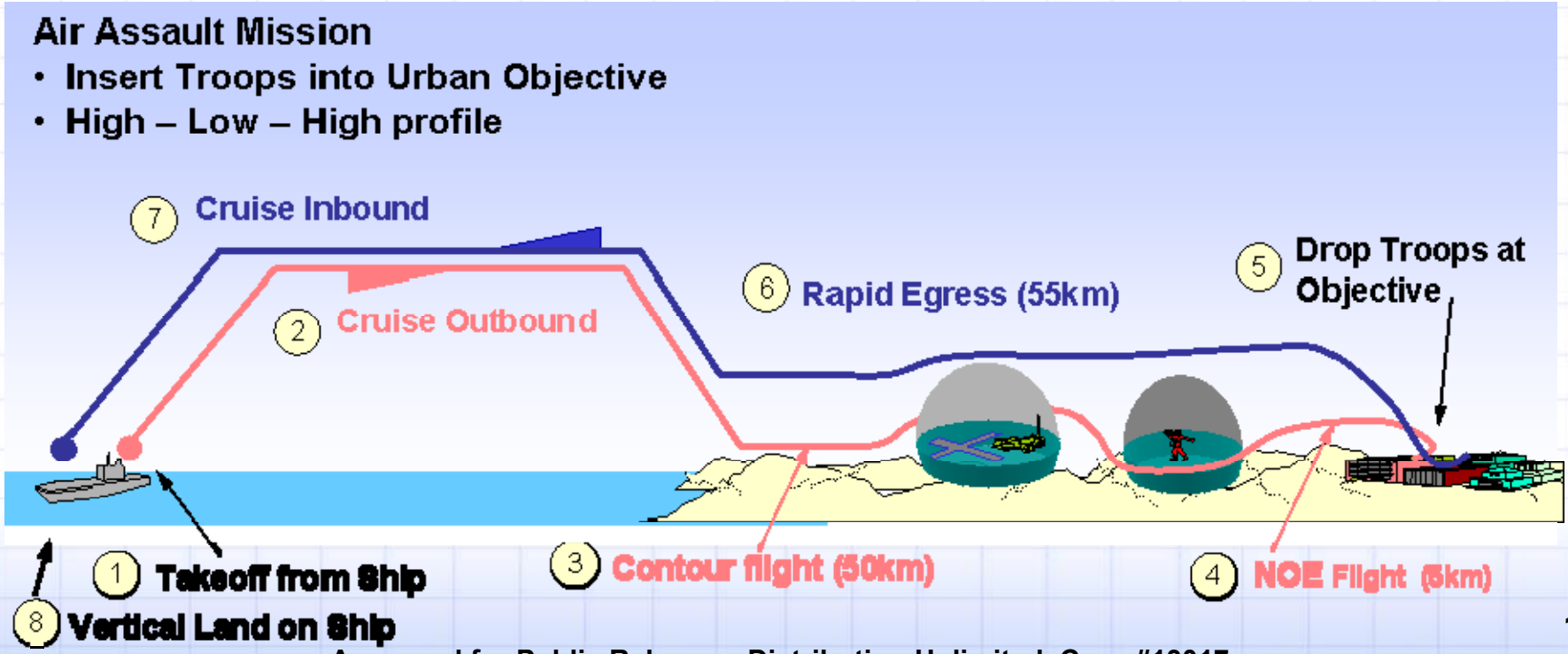
Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor

Mission Application Example *(1 of 3)*

Ideal Attributes Vary by Mission Segment

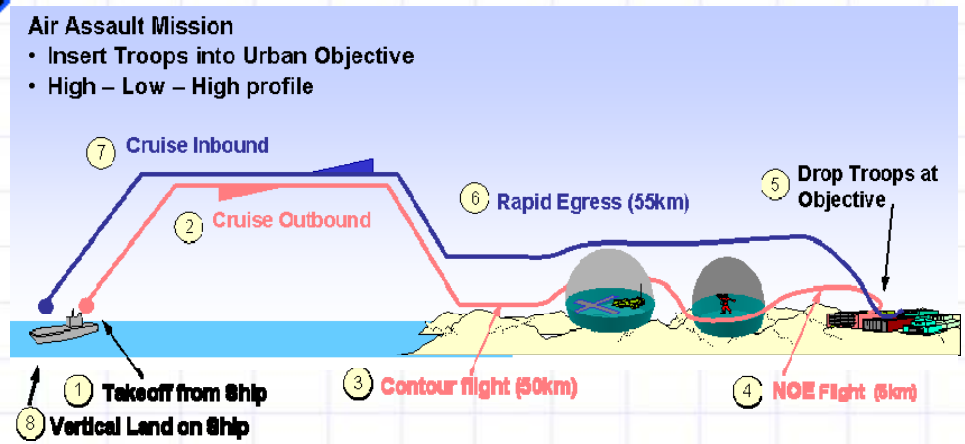
- High Lift – Takeoff, Midpoint Hover, Landing
- Efficient Cruise – Outbound, Inbound
- Highly Maneuverable – Contour Flight
- Low Noise – Approach to Objective
- High Speed – Egress

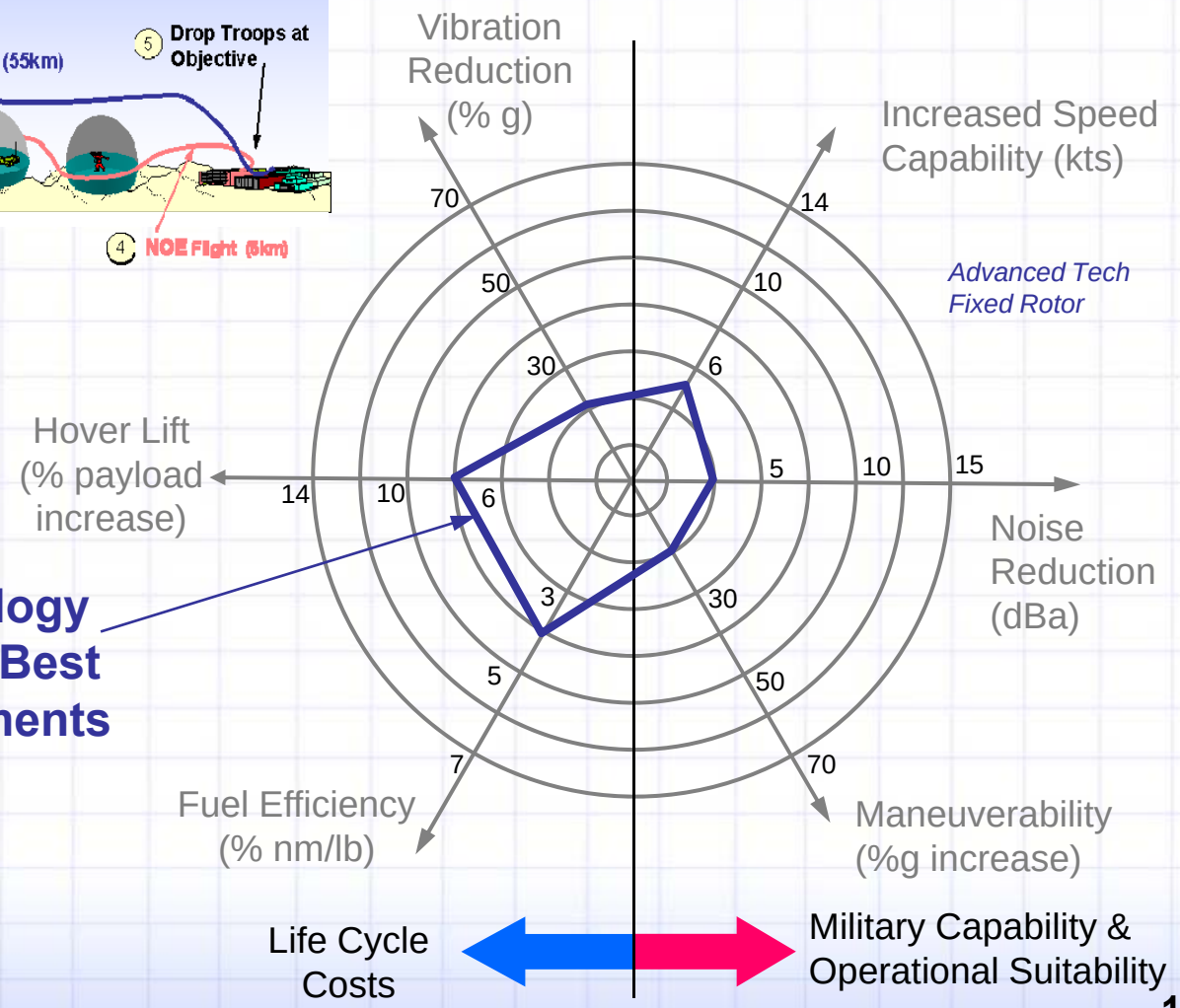


Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor

Mission Application Example *(2 of 3)*





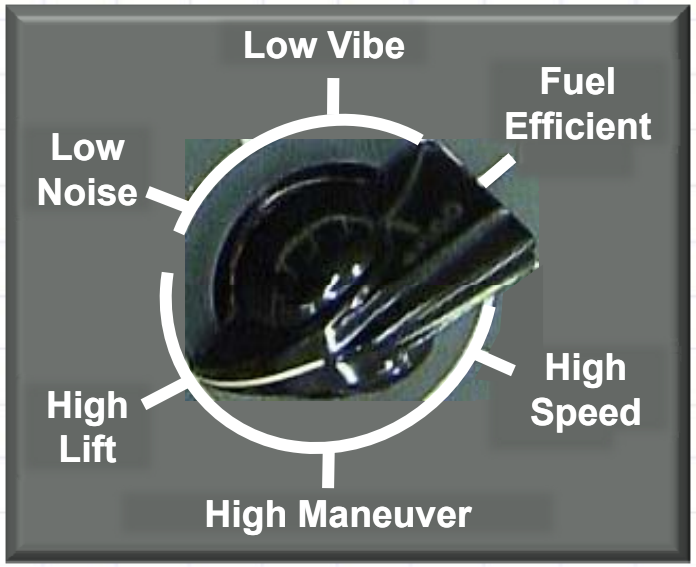
Define Advanced Technology Fixed Geometry Rotor as Best Compromise Across Segments

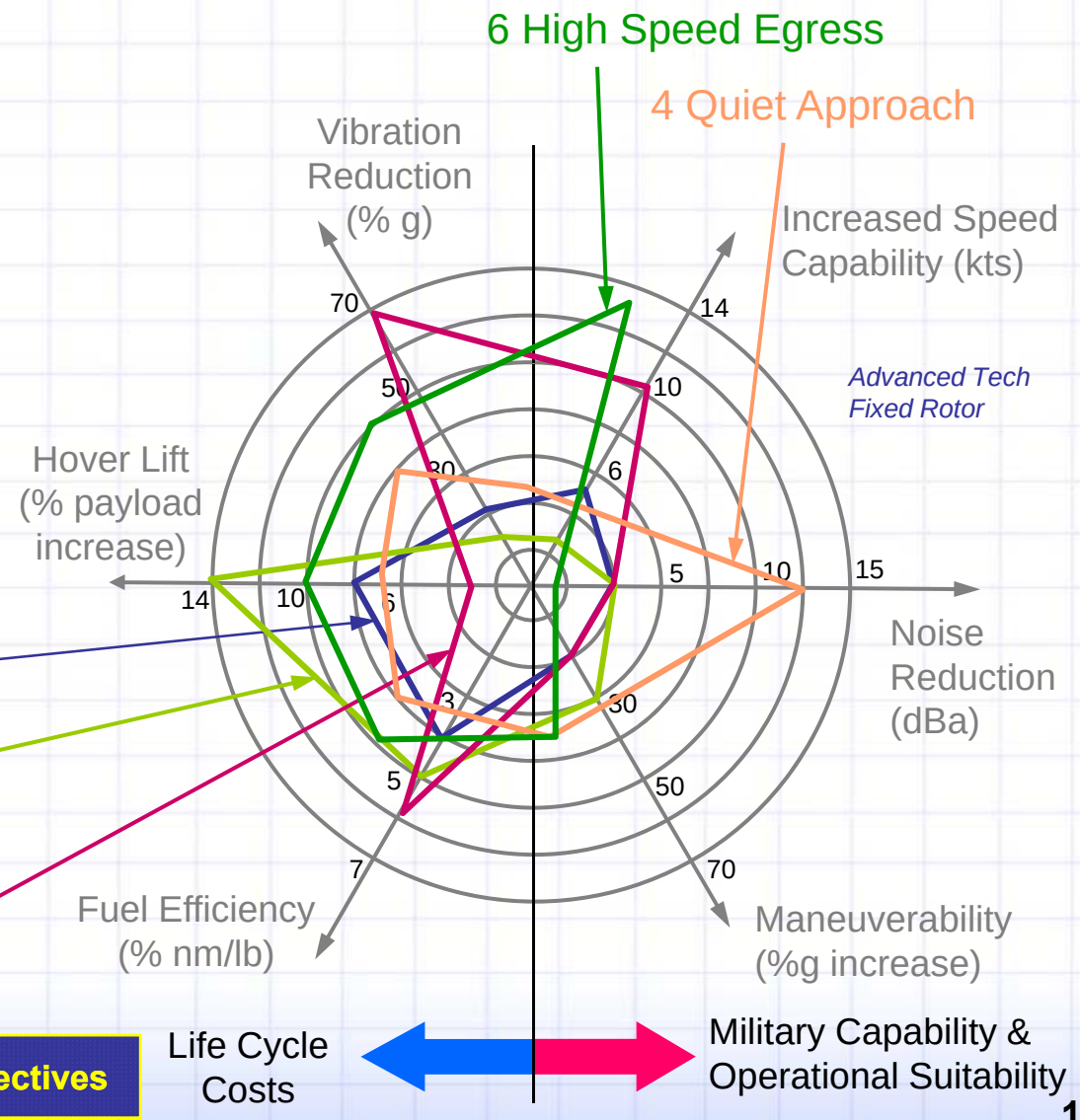
Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor

Mission Application Example (3 of 3)

Implementation/Human Interaction To Be Defined





Advanced Technology Fixed Geometry Rotor

1 High Lift Takeoff
5 Midpoint Hover
8 Efficient Landing

2 Outbound Cruise
7 Inbound Cruise

Optimize Rotor Attributes for Segment Objectives

Life Cycle Costs ⟷ Military Capability & Operational Suitability

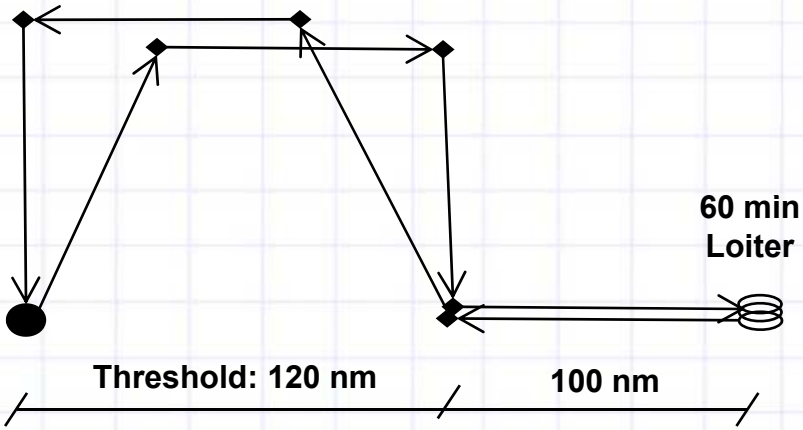
Approved for Public Release – Distribution Unlimited, Case #13017

Example Reference Missions

Army Attack/Recon Mission

Assumptions/Requirements

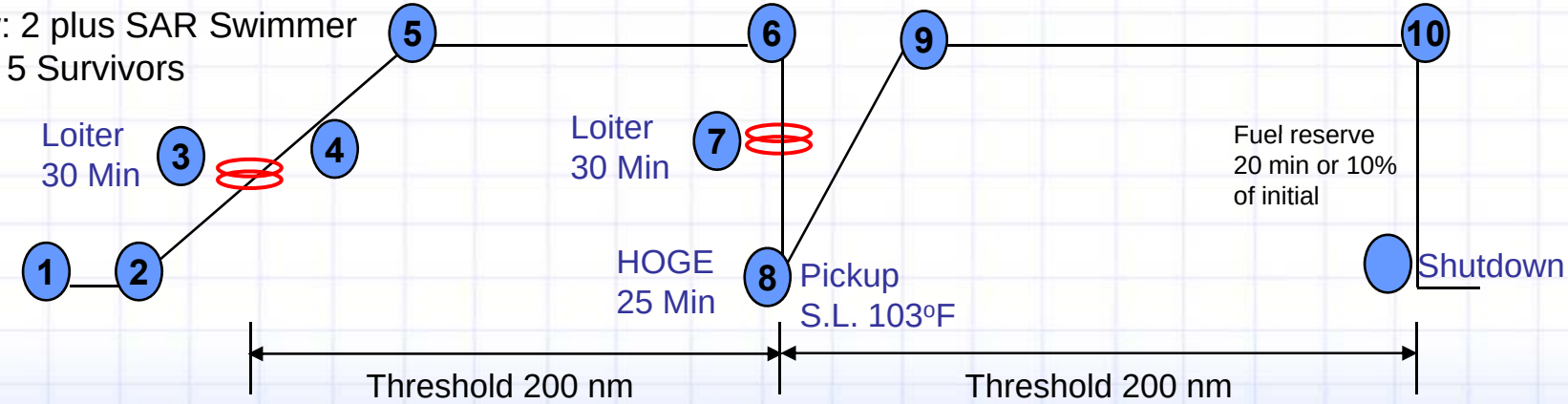
- Basing Location: Airfield
- ROA: 300 nm with 60 Minutes TOS
- Operational Munitions Payload: 3400 lbs
- 500 fpm VROC at 4,000 ft PA/95°F Fully Armed and Fueled



Navy Carrier Plane Guard/SAR Mission

Assumptions/Requirements

- Basing Locations: CV, LHA, LHD, LPD-class ships
- ROA: 200 nm (currently between 10-50 nm)
- Search Time: 30 Minutes
- Crew: 2 plus SAR Swimmer
- Load 5 Survivors



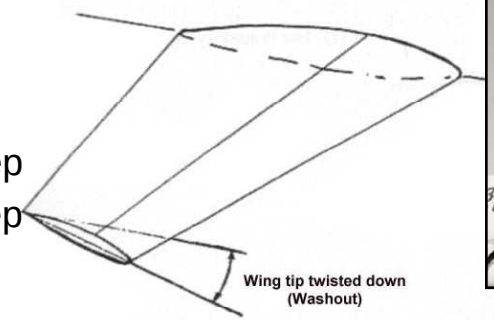
fpm = feet per minute; HOGE = hover out of ground effect; min = minutes; nm = nautical mile; PA = pressure altitude; ROA = radius of action; SAR = search and rescue; TOS = time on station; VROC = vertical rate of climb; VTO = vertical take-off

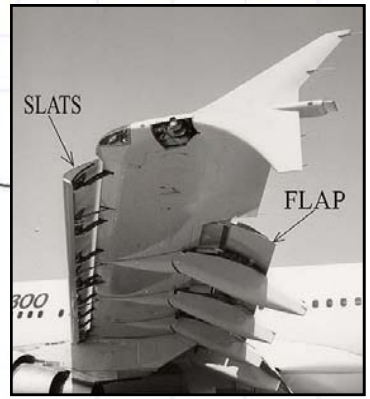
Mission Adaptive Rotor

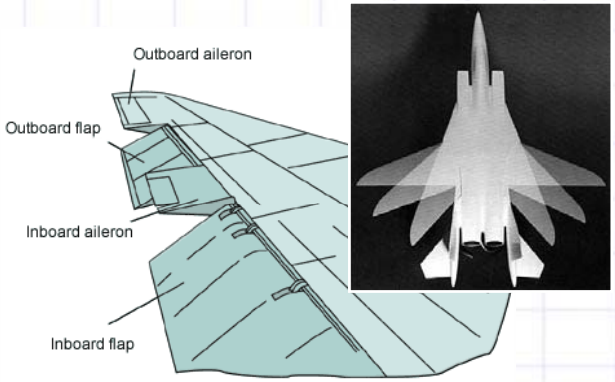
What Makes Rotary-Wing Adaptation So Hard?

Successful Fixed Wing Adaptations

- **Planform**
  - Taper
  - Sweep
  - Variable Sweep
  - Forward Sweep
- **Section**
  - Airfoil
  - Twist ("Wash-in")
- **High Lift Devices**
  - Flaps
  - Slats
  - Spoilers
- **Control Surfaces**
  - Ailerons
- **End Plates**

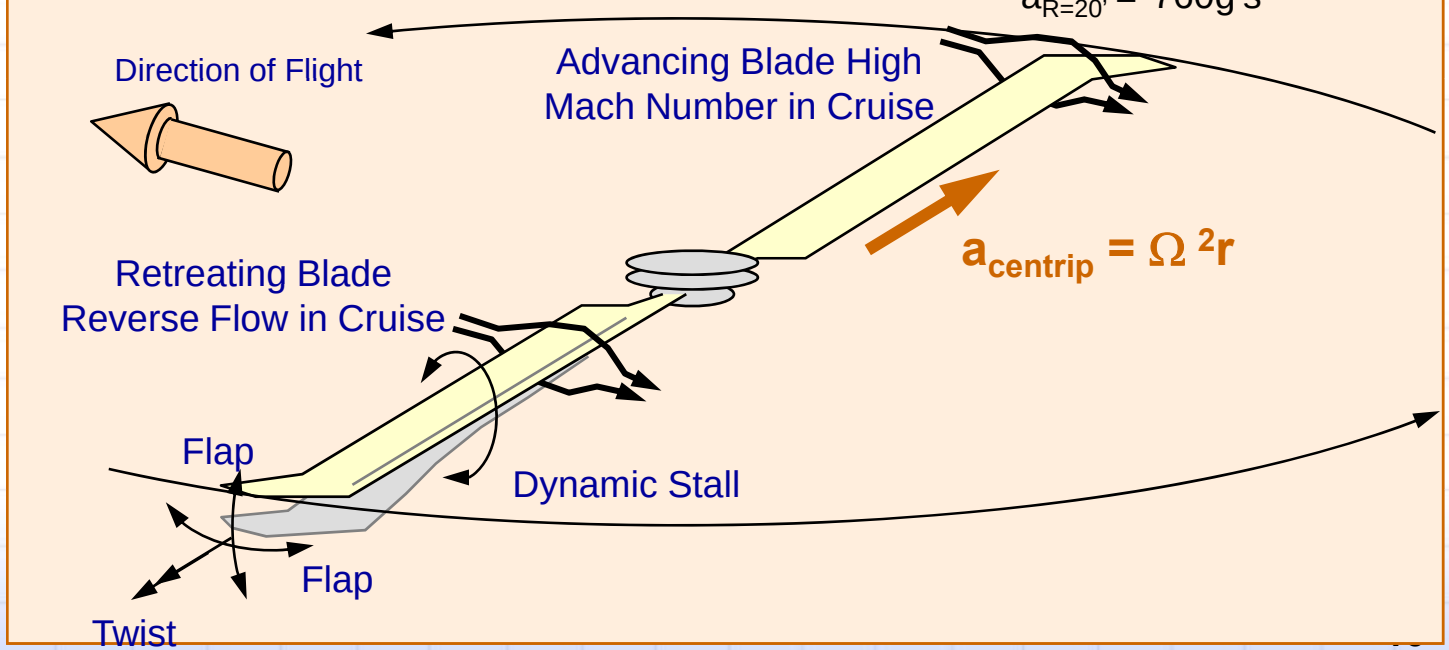






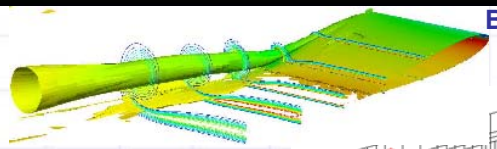
Rotary-Wing Challenges

For V_{tip} = 700fps
$a_{R=20'}$ = 760g's

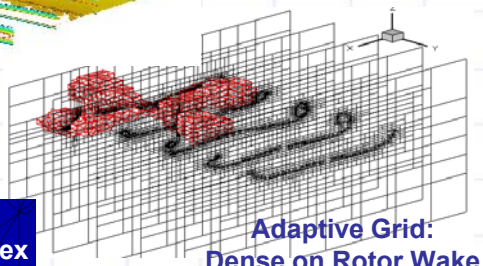


Helicopter Quieting Program (HQP)

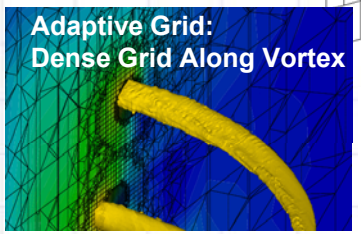
- HQP Tool Suites
  - Coupled Aeromechanic Analysis / CFD
  - Reynolds-Averaged Navier Stokes
  - Adaptive Grids
  - Turbulence model to capture non-linear aerodynamic flow field effects near blade
  - Improved Far-Field Rotor Wake Location
- Demonstrated Correlation
  - Out-of-the-Box Correlation for Conventional Rotors
  - Calibration Against Advanced Rotors
- Mission Modeling Tools to Determine Tactical Significance
  - Acoustic "Johnson Criteria"
  - Acoustic Design Criteria
  - TTPs / Pilot Technique



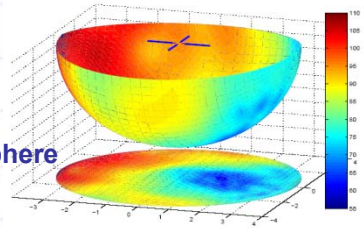
Blade Tip Vortex Flow



Adaptive Grid:
Dense on Rotor Wake

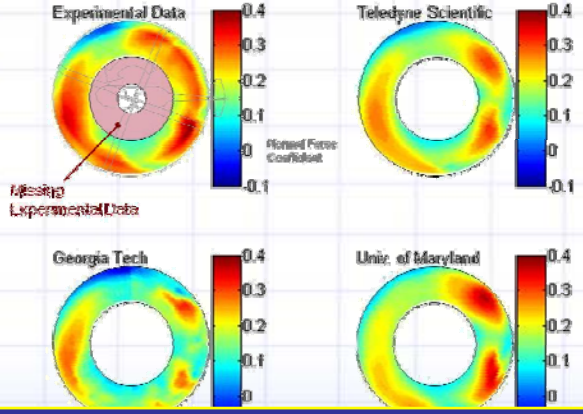


Adaptive Grid:
Dense Grid Along Vortex



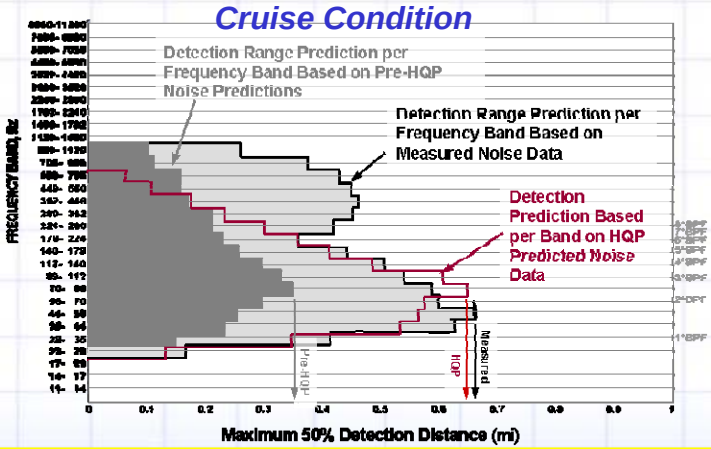
Noise Hemisphere

UH-60 Normal Force –
Mid-Speed Level Flight with Dynamic Stall



HQP Tools Accurately Predict Rotor Forces in Presence of Non-Linear Aerodynamic Events

SMART Rotor Detection Range –
Cruise Condition



HQP Tools Dramatically Improve Novel Rotor Acoustic Detection Range Prediction

Approved for Public Release – Distribution Unlimited, Case #13017

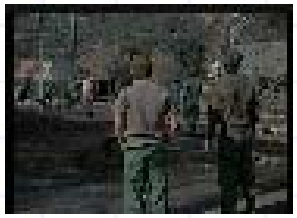
Reduced Acoustic Signature

Military Utility

Mission Adaptive Rotor will develop and demonstrate dramatic improvements in rotor performance, sustainability/availability, and survivability over current systems through a dynamically optimized configuration

HQP analytical tools provide accurate acoustic prediction for rotors *enabling acoustics* to be a *key performance parameter* in rotorcraft design

The single biggest threat to rotary wing aircraft in current conflicts is small arms fire, cued by the human ear. Eliminating the acoustic signal limits rotorcraft exposure to enemy fires!



MAR Comp. Video

Approved for Public Release – Distribution Unlimited, Case #13017

Notional Survivability Improvement

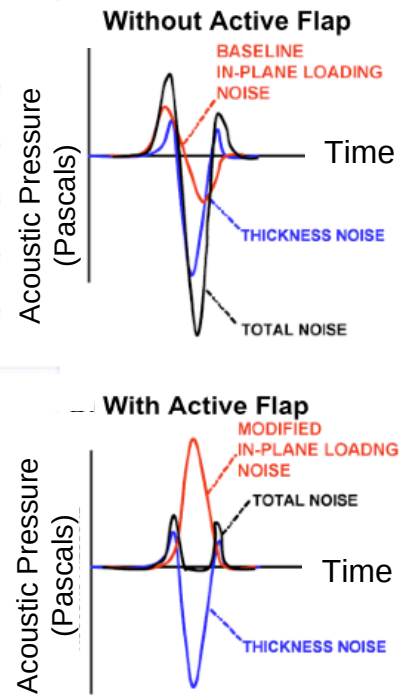
Reduced Noise Footprint

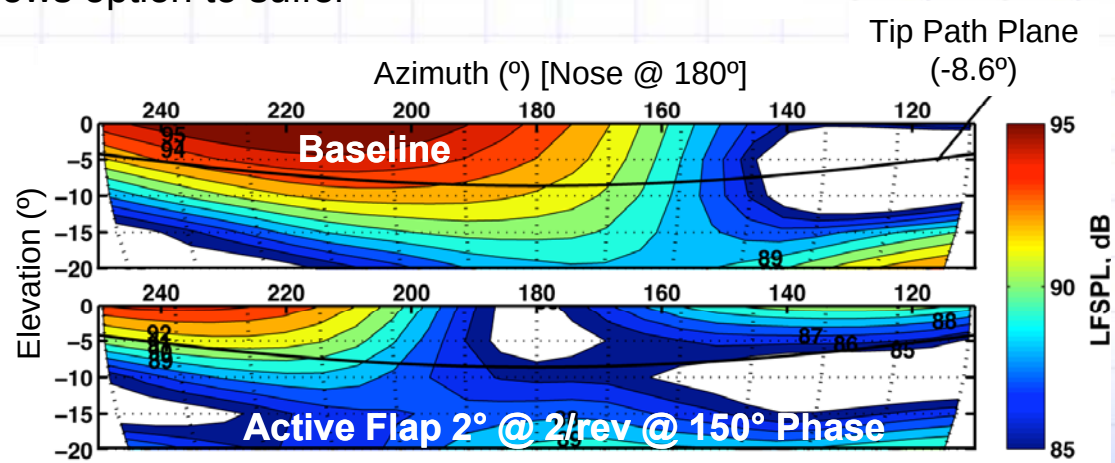
Reduced Susceptibility

- On-blade active-devices can reduce early aural detection
  - In-plane noise typically dominated by negative thickness noise peak (nominal condition at moderate airspeed)
  - On-blade active devices can be highly effective at reducing in-plane rotor noise (low frequency tones)
  - Can generate loading noise “anti-pulse”
  - Modify azimuthally-varying blade dynamics and aerodynamic forces
  - Partially reduce (negative) thickness noise peak
- Rotor design for reduced susceptibility with smaller impact
  - Improving legacy system achieves small benefit at notable “cost”
  - “Inter-mission” adaptation (kits) allows option to suffer consequences when appropriate … otherwise provisions, only
  - Provisions made at initial design have minimal/zero cost

Reduced Vulnerability

- Adaptability to operate safely (degraded mode) with damage





Notional Performance Improvement

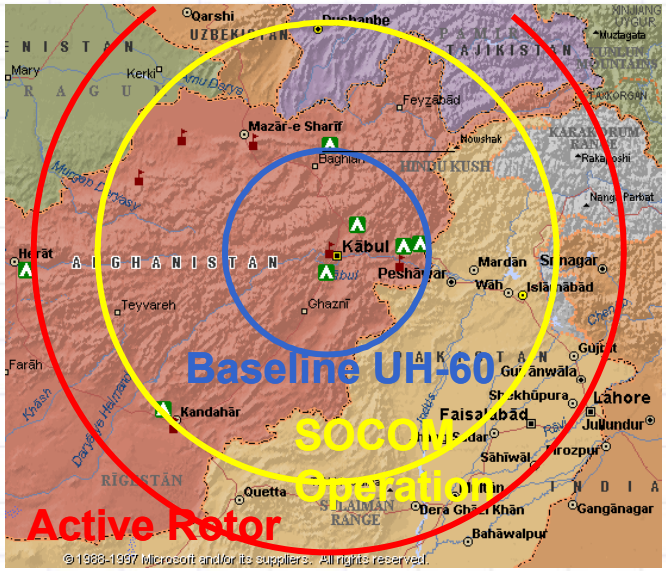
Increased Lift, Speed, Range

Example: Variable Leading Edge

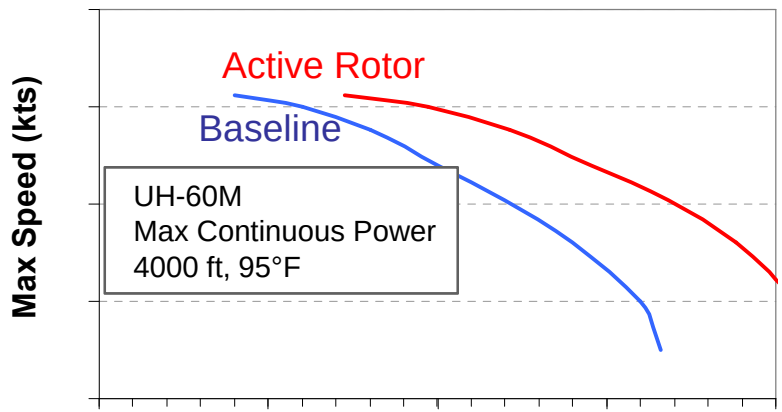
- Improved L/De by ~3%
- Reduced 4/rev vertical force component by ~8%
- Reduced pitching moments

Example: Active Slat as Retrofit to USASOC MH-60

- ~20% Increase in Speed @ Takeoff Gross Weight
- ~40% Increase in Speed @ Max Alt Gross Weight
- ~20% Increase in Thrust @ 120 kts
- ~45% Increase in Range



MH-60K Max Speed Improvement with Active Rotor



Approved for Public Release – Distribution Unlimited, Case #13017

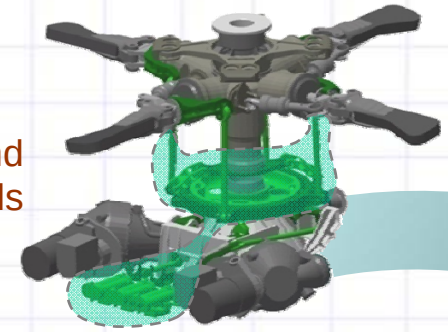
Notional Supportability Improvement

Reduced Complexity and Vibration

Example: On-Blade Controls

- Electric Rotating-to-Non-rotating Transfer … *Wireless?*
- Eliminate Swashplate & Mechanical Links

Current Servo and Swashplate Controls



Example: Higher Harmonic Control (HHC) for More Benign Operating Environment

- Reduced Loads
- Reduced Vibration
  - > 80% demonstrated in small scale wind tunnel testing
  - Potential for zero vibratory hub loads

Approved for Public Release – Distribution Unlimited, Case #13017

MAR Potential Benefits

Performance

- Hover Agility
- Cruise Speed
- Cruise Efficiency
- Payload
- Range
- Maneuverability
- Endurance
- Autorotation

Survivability and Safety

- Acoustics, etc
- Ballistics, crash worthiness, etc
- Brown-out / White-out
- Compensation for damage

Availability

- Vibration (including 1/rev for active track and balance)
- Affordability
- Serviceability
- Maintainability
- Marinizability
- Durability
- Reliability
- Data/Power transfer
- Load reduction to increase component life – reduce weight

Approved for Public Release – Distribution Unlimited, Case #13017

Mission Adaptive Rotor
Technical Challenges

Novel and Large Reconfiguration Envelope

- Requires effector invention, development, and a large amplitude not currently available
- Must deal with aero-servo-elastic implications

Intelligent Autonomous Adaption

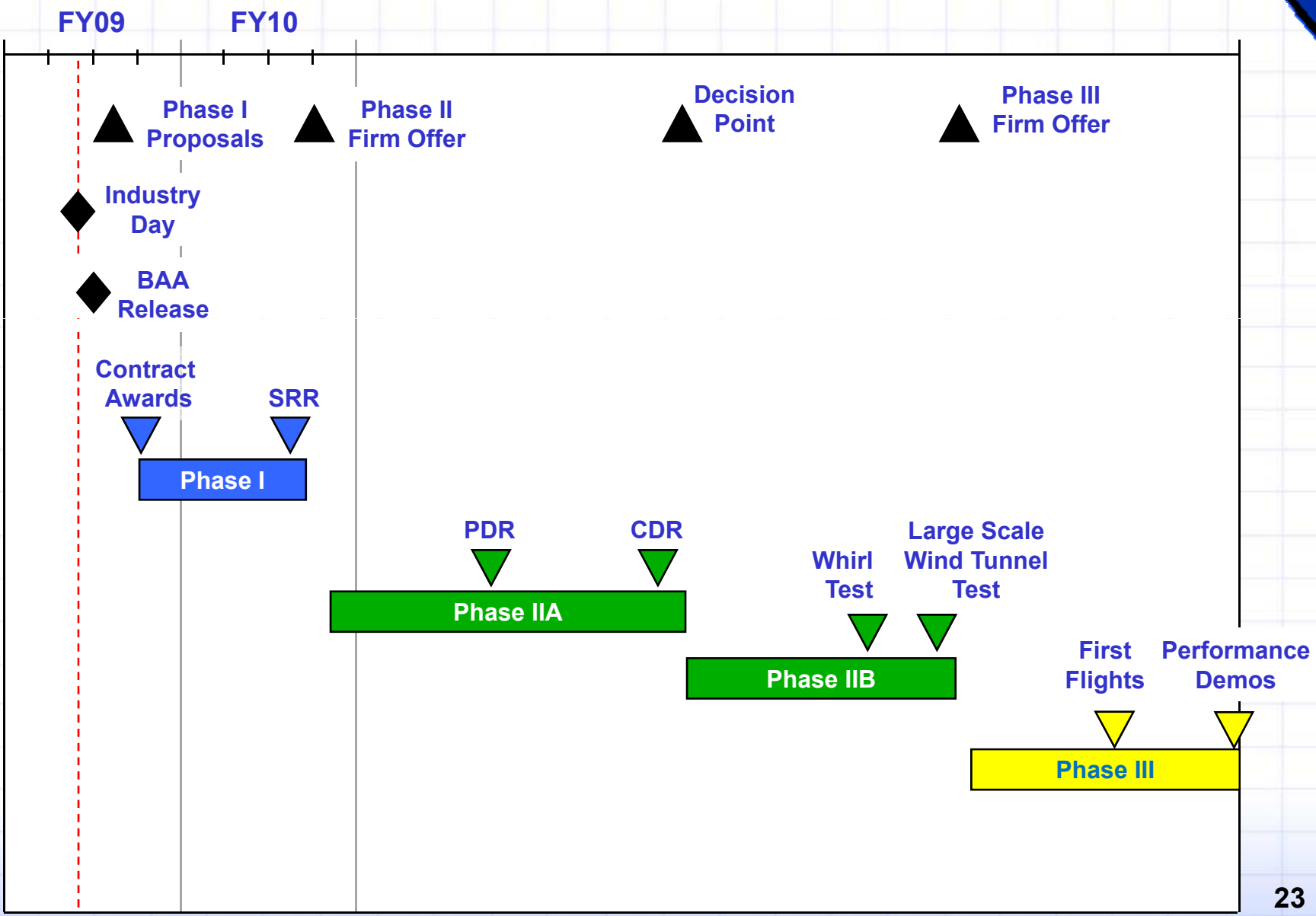
- Required both before and during mission
- Capability enables achieving mission objectives
- Performance optimization as well
- Multiple time scales: stability and response, trajectory and guidance, mission, service life

Efficient and Optimized Design

- Adaptation adds many dimensions to capability, hence adds these dimensions to design space
- Need efficient methods to explore, refine, optimize design

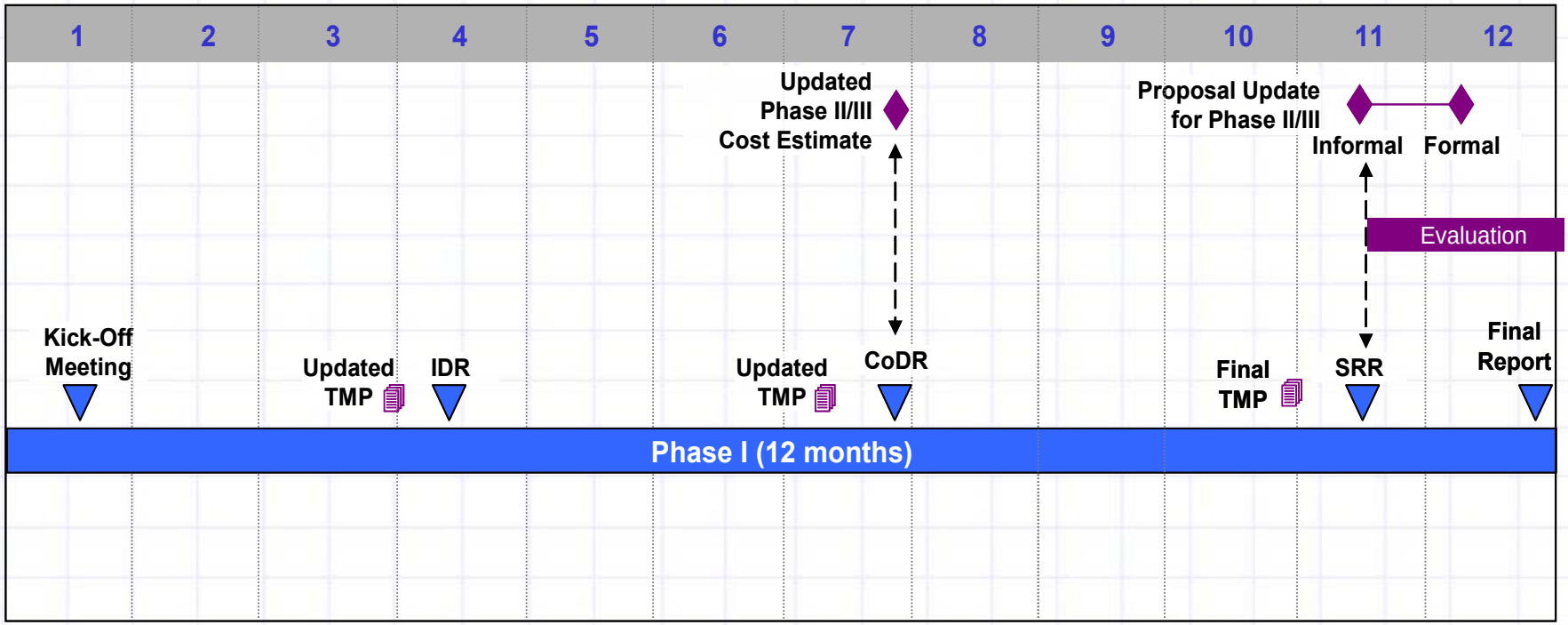
Approved for Public Release – Distribution Unlimited, Case #13017

Notional MAR Program Schedule



Approved for Public Release – Distribution Unlimited, Case #13017

Notional MAR Phase I Schedule

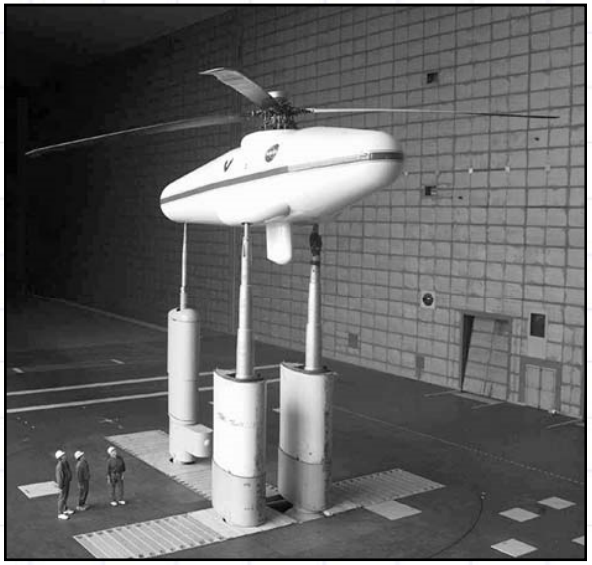


IDR = Interim Design Review
CoDR = Conceptual Design Review
SRR = System Requirement Review
TMP = Technology Maturation Plan

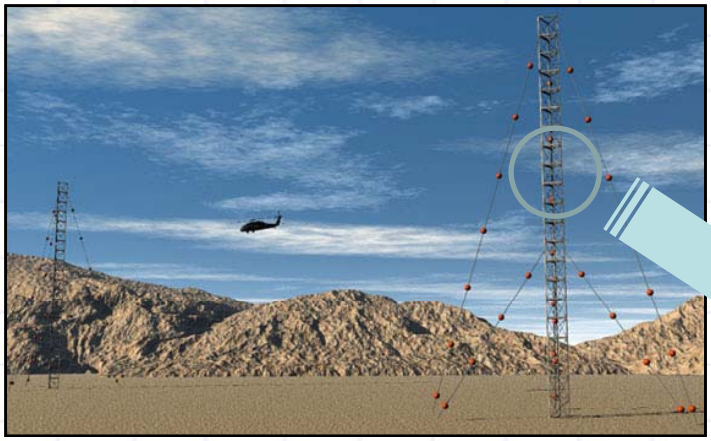
Approved for Public Release – Distribution Unlimited, Case #13017

Example Phase II Govt Facilities

Bidders Must Balance Risk Reduction and Cost



Air Force National Full-Scale Aerodynamics Complex (NFAC) at NASA Ames



Air Force Aeroacoustic Research Complex (ARC) at White Sands Missile Range

ARC Site Microphone

Air Force Research Laboratory (AFRL) Whirl Stand at Wright-Patterson Air Force Base

Approved for Public Release – Distribution Unlimited, Case #13017

Example Phase III Flight Test Platforms

Notional Thrust Class (Per Rotor)

Bidders Must Balance Residual Risk and Cost

Bell UH-1Y / AH-1Z
USMC
Max TO wt: 18,500 lb

Sikorsky H-60 Black Hawk / Seahawk
US Army, USN, USSOCOM, USCG
Max TO wt: 24,500 lb

Lockheed Martin VH-71 Kestrel
USMC
Max TO wt: 34,320 lb

Boeing AH-64 Apache
US Army
Max TO wt: 21,000 lb

Bell Boeing V-22 Osprey
USMC, USSOCOM
Max VTO wt: 52,600 lb
Max wt per rotor: 26,300 lb

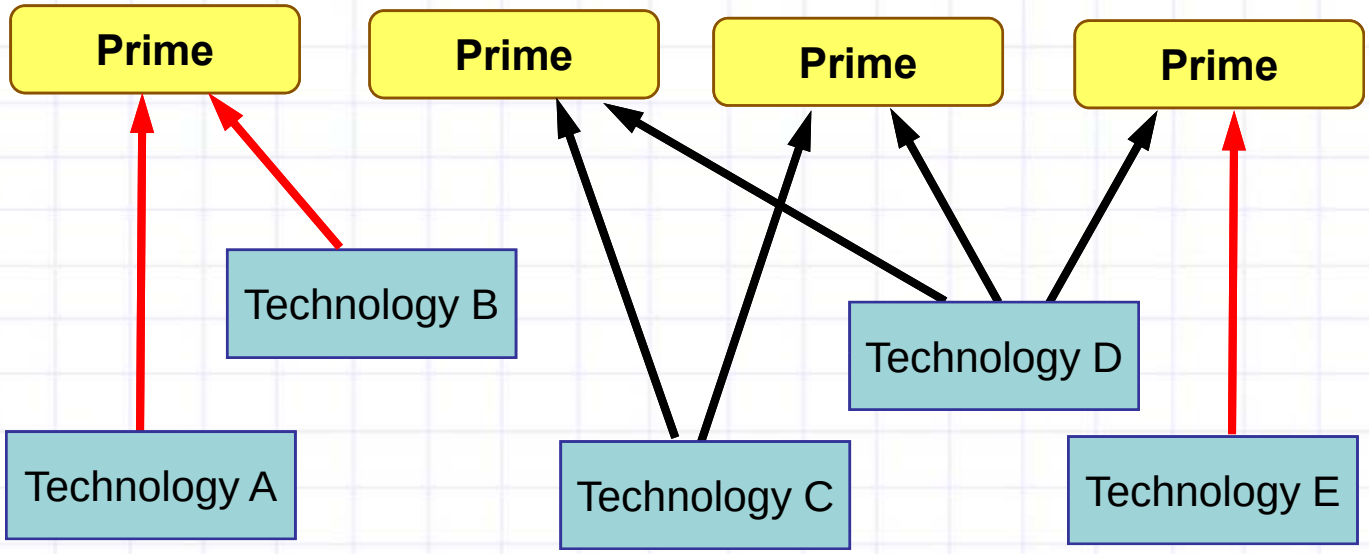
Boeing H-47 Chinook
US Army, USSOCOM
Max TO wt: 54,000 lb
Max wt per rotor: 27,000 lb

18K lb ← Lift per Rotor *(GTOW / Lifting Rotors)* → **36K lb**

Approved for Public Release – Distribution Unlimited, Case #13017

"It's about the technologies, folks!"

- DARPA encourages prime offers to evaluate a range of technologies.
- DARPA encourages technology providers to support multiple efforts.



Summary

MAR has potential to demonstrate the critical rotor technologies for the next generation rotorcraft

Working closely with other government rotorcraft stakeholders

- Navy/Marine Corps
- Army
- Air Force
- SOCOM
- NASA

The potential BAA will provide wide latitude for a range of technology and program options

Industry Day is intended for feedback on our objectives and provide opportunities for networking

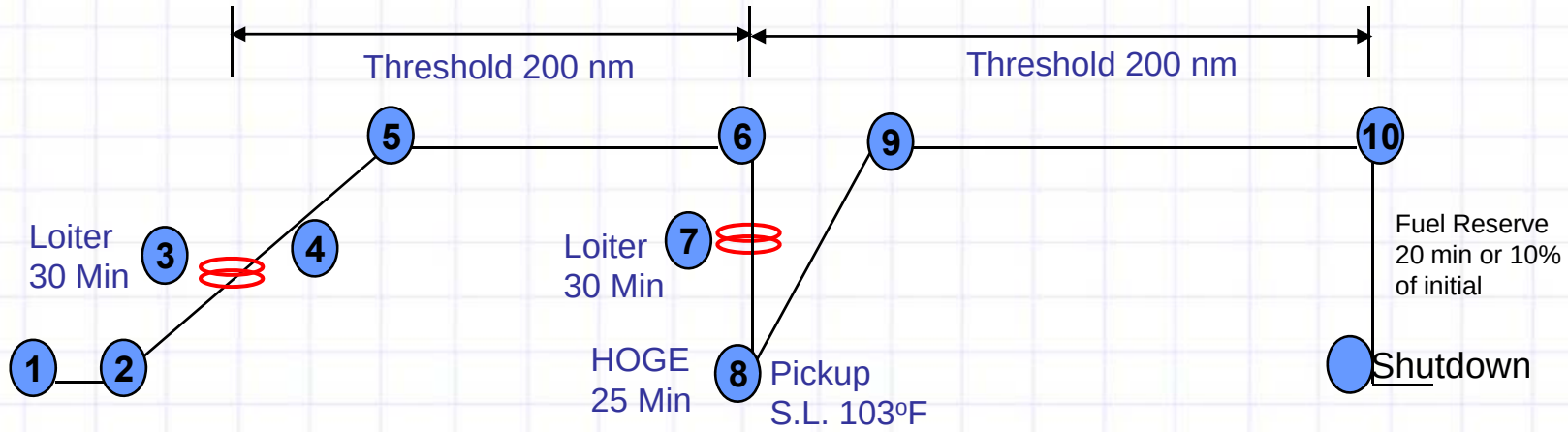
Approved for Public Release – Distribution Unlimited, Case #13017

Reference Missions

Distribution Statement A: Approved for Public Release, Distribution Unlimited, Case #13017

Reference "Navy Mission"

Carrier (CV) Plane Guard/SAR



Segment 1
Taxi / Warm-up
8 Minutes
Alt: Sea level
Temp: 103ºF

Segment 2
Ship Based VTO
Climb to Altitude
No Range Credit
applied to Maneuver

Segment 3
Loiter
Alt: 500 ft AGL
Vel: V_{be}
Time: 30 min

Segment 4
Climb to Altitude
Range Credit
applied to Maneuver

Segment 5
Ingress
Alt: Best Dash
Vel: Dash
Dist: 200 nmi

Segment 6
Descend
No Range Credit for Descent
Alt: Best Dash

Segment 7
Loiter and Descent
No Range Credit for Descent
Alt: 500 ft AGL
Vel: V_{be}
Time: 30 min

Segment 8
HOGE and Pickup 5
Survivors,
Climb to Altitude
Time: 25 min
Alt: 70 ft AGL @ S.L.
Temp: 103ºF

Segment 9
Egress
Alt: Best Dash
Vel: Dash
Dist: 200 nm

Segment 10
Landing
No Range Credit for Descent
Alt: Sea level
Temp: 103ºF

Sensor package
Multi-Mode
(Surface Search
w/ISAR) Radar
Weather Radar
FLIR
ESM
Load: 1,000 lb
Cruise Airspeed:
150 kts (B)
Dash Airspeed:
175 kts (B)

Sea Level/103 ºF/No Wind

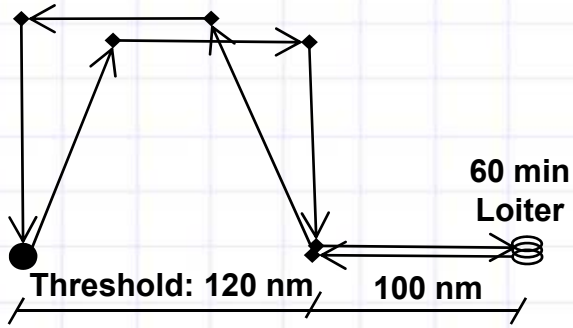
Assumptions/Requirements
- Basing Locations: CV, LHA, LHD, LPD-class ships
- ROA: 200 nm (Currently between 10-50 nm)
- Search Time: 30 Minutes
- Crew: 2 plus SAR Swimmer
- Load 5 Survivors

AGL = above ground level; HOGE = hover out of ground effect; sl = sea level; VBE = best endurance velocity; ROA = radius of action; SAR = search and rescue; VTO = vertical take-off

Approved for Public Release – Distribution Unlimited, Case #13017

Reference "Army Mission"

Attack/Recon



Assumptions/Requirements

- Basing Location: airfield
- ROA: 300 nm with 60 Minutes TOS
- Operational Munitions Payload: 3400 lbs
- 500 fpm VROC at 4,000 ft PA/95°F Fully Armed and Fueled

	Segment	Time	Distance	Speed	Atmosphere		Payload		Power	
					Alt	Temp	Wt	Δsq-ft	Eng. Spec	Margin
1	Warm-up	5 min			4k ft	95.0 ºF	3400 lb	10.0	100% IRP	
2	VTO	1 min		HOGE	4k ft	95.0 ºF	3400 lb	10.0	100% MRP	500 fpm VROC
3	Climb		Credit to 4	V_{CL}	ISA		3400 lb	10.0	100% IRP	
4	Cruise		120 nm	V_{BR}	Best	ISA	3400 lb	10.0	100% MCP	
5	Descent	No Fuel Burn Credit			ISA		3400 lb	10.0	100% MCP	
6	Ingress		100 nm	V_P	4k ft	95.0 ºF	3400 lb	10.0	90% MCP	
7	Loiter (Quiet Mode)	60 min		V_{BE}	4k ft	95.0 ºF	3400 lb	10.0	100% MCP	
8	Egress		100 nm	V_P	4k ft	95.0 ºF	0 lb	0.0	90% MCP	
9	Climb		Credit to 10	V_{CL}	ISA		0 lb	0.0	100% IRP	
10	Cruise		120 nm	V_{BR}	Best	ISA	0 lb	0.0	100% MCP	
11	Reserve (c)	20 min		V_{BR}	4k ft	95.0 ºF	0 lb	0.0	100% MCP	

fpm = feet per minute; HOGE = hover out of ground effect; IRP = intermediate rated power; ISA = International Standard Atmosphere; k ft = thousands of feet; MCP = maximum continuous power; nm = nautical mile; PA = pressure altitude; TOS = time on station; VBE = best endurance velocity; VBR = best range velocity; VCL = climb velocity; VP = penetration velocity; VROC = vertical rate of climb; VTO = vertical take-off

Notes:

For Aircraft w/ MAR technology desire ability to perform mission at 6k/95

V_{BR} – 99% Best Range Speed

V_P – Penetration Speed (90% MCP)

Loiter in Configuration for Minimum Acoustic Signature

Drop Ordinance at End of Loiter Segment

Remove Drag Increment for Ordinance if Internal Carriage Design

Approved for Public Release – Distribution Unlimited, Case #13017