EXECUTIVE SUMMARY

29TH ANNUAL AHS INTERNATIONAL DESIGN COMPETITION
UNDERGRADUATE CATEGORY

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Sikorsky
A United Technologies Company

CONCEPT DESIGN SUMMARY

BADGER SPECIFICATIONS

WEIGHTS	Units	Value	
Empty Weight	lbs	2148	
Max. Gross Weight	lbs	2800	
GTOW	lbs	2500	
Payload	lbs	300	
Max. Fuel Weight	lbs	127	
PERFORMANCE @ S.L. 103 F	**Units**	**GW 2500 lbs**	**GW 2800 lbs**
Max. Cruise Speed	kts	175.9	174.2
Speed at 90% MCP	kts	165.7	164.1
Best Range Speed	kts	119.8	123.6
Best Endurance Speed	kts	68.6	73.1
Max. Sideward Flight Speed	kts	65.5	37
Max Sustained Load Factor	G	3.11	
Course Time	s	247.8	
POWER PLANT	**Units**	**Value**	
Number of Engines		1	
MRP @2 min 103°F S.L	hp	550	
MCP @ 103°F S.L	hp	424	
GENERAL DIMENSIONS	**Units**	**Value**	
Number of Blades (per rotor)		2	
Main Rotor Diameter	ft	24.8	
Main Rotor Blade Chord	ft	0.66	
Main Rotor Disk Loading	lbs/ft^2	2.58	
Tip Speed	ft/s	670	
Propeller Diameter	ft	6	
Flat Plate Area Forward Flight	ft^2	7	
Flat Plate Area Sideward Flight	ft^2	41	

A NEW TWIST ON INTERMESHING

- This ain't your mama's "air mule"
  Fact: The Badger is no simple "air mule".
  It has been designed to be a fast and maneuverable pylon racing helicopter

	Badger	K-Max: the "Air Mule"
Max speed @ SL STD	170 Knots	100 Knots
Translational speed	63 Knots	11.9 Knots
Max TOGW	2500 lbs	12000 lbs
Power	400 hp	1500 hp
Disk loading	2.59 lbs/ft²	3.28 lbs/ft²
Diameter	24.8 ft	48.25 ft
Overall Length	25 ft	52 ft
RFP η/Max TOGW (without time)	$.476 = \frac{5 * 128lbs + 550hp}{2500lbs}$	$.75 = \frac{5 * 1492lbs + 1500hp}{12000}$

ACKNOWLEDGEMENT OF REQUIREMENTS

•PERFORMANCE

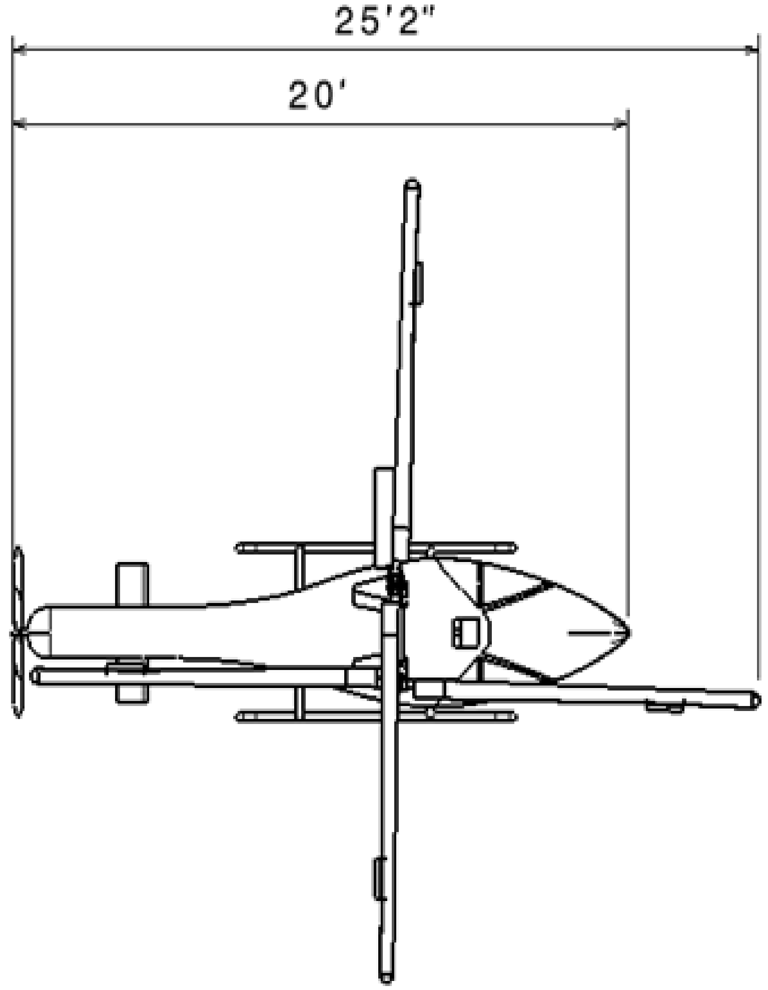
- Max start speed <100 kts
- Max bank angle of 90°
- Slung load capabilities
- HOGE take off @S.L. 103°F , TOGW
- Cruise at min of 125 kts @90 % MCP
- 60 kts SW flight @ S.L 103°F, TOGW
- Time Estimates
- Fuel burned throughout mission
- η Function

•MISSION

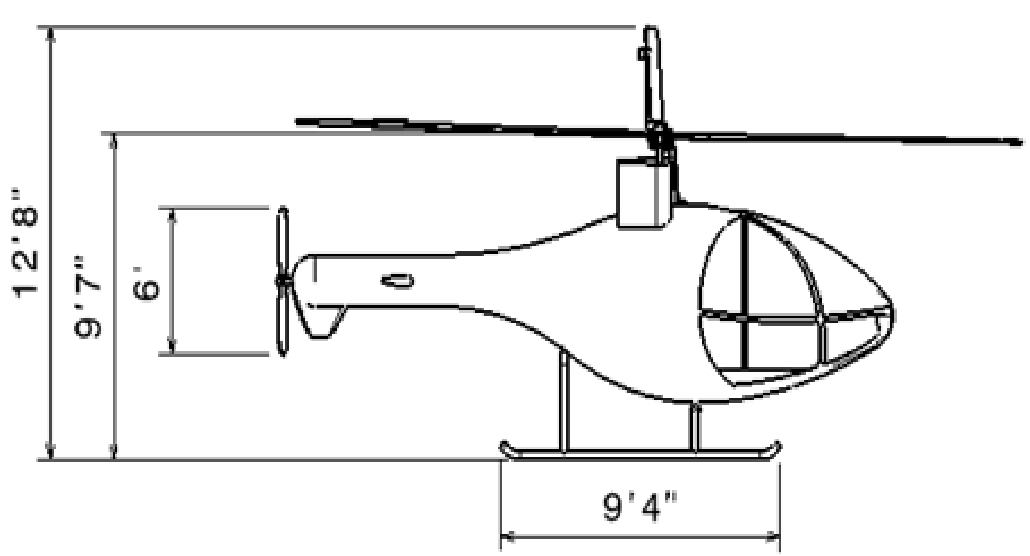
- One 225 lbs pilot
- 10 min warm up time
- 5 min to takeoff
- 15 min fuel reserve @V_{BR}
- 15 ft safety zone
- Minimum clearance of one rotor radius from moving components
- MIL STD 850B visibility
- Floatation/Fire protection for pilot

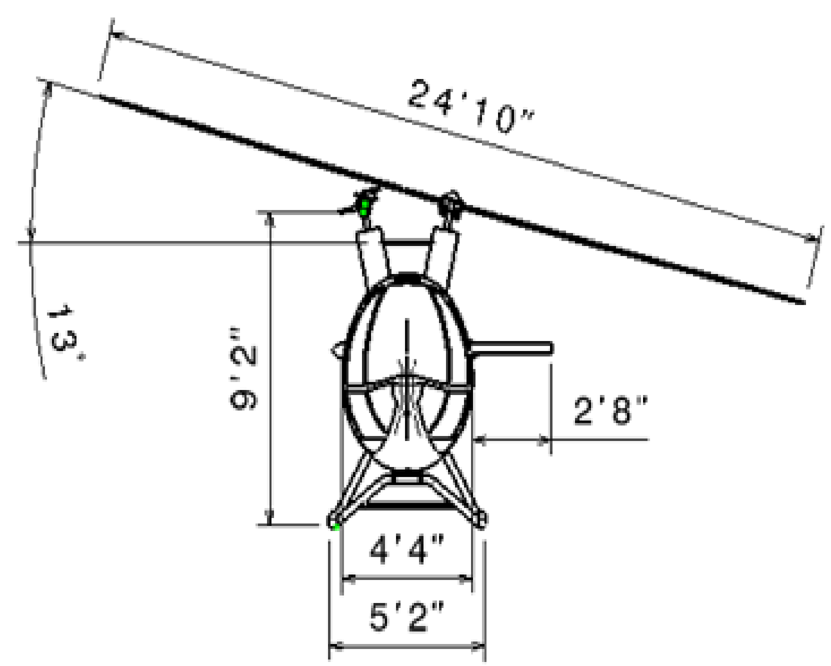
•MISCELLANEOUS

- Accounted power installation factors
- Inboard/outboard profiles of helicopter
- Weight allocations for all components (MIL STD 1374)
- Pilot feedback
- Preliminary structural design
- Avionics suite meeting min FAA req. for NY VFR corridor



GT BADGER





DIMENSIONS

Length Overall	25.17 ft
Overall height	12.67 ft
Fuselage width	4.33 ft
Rotor diameter	24.8 ft
Disk loading	2.58 lbs/ft^2

ENGINE RATING

(ISA, S.L. 103°)

Number of Engines	1
MCP	424 hp
MRP @ 2 min	550 hp

WEIGHT

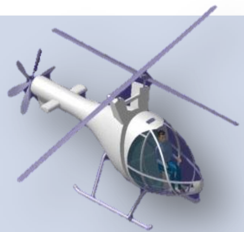
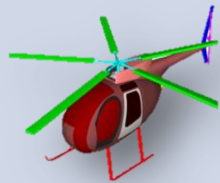
Max. TOGW	2800 lbs
Empty	2148 lbs
Max. Fuel	127 lbs
Crew	225 lbs
Slung payload	300 lbs

PERFORMANCE

TOGW@ 2500 lbs (ISA, S.L. 103°)

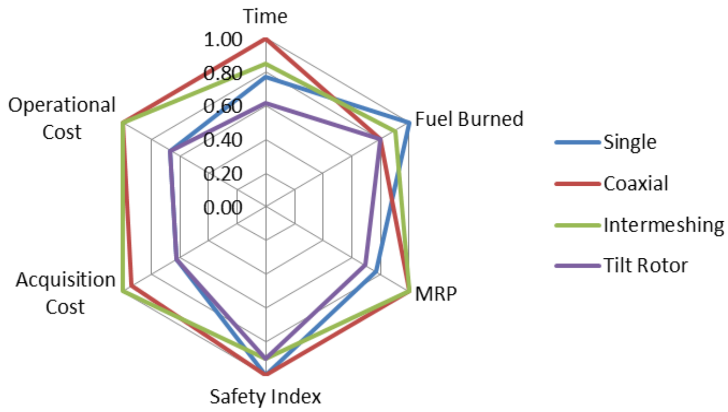
Best endurance speed	68.4 kts
Best range speed V_{BR}	119.8 kts
Max. speed	175.9 kts
Speed at 90% MCP	165.7 kts
Sideward Flight Speed	65.5 kts

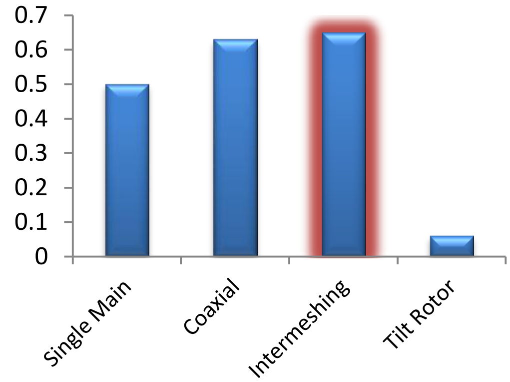
INTERMESHING DECISION


Intermeshing compared to:	Single Main	Coaxial
Pros	-True lift symmetry in forward flight -Smaller fuselage length -Very easy on the pilot -No tail: more power for main rotors	-No limitations due to risk of blade tips striking each other -Significantly simpler transmission -True lift symmetry in forward flight -Better sideward flight due to canted rotors -Very easy on the pilot in terms of controls - Lower Induced HP Required
Cons	-Higher drag -Higher HP Required -Not as much control in yaw	-Slightly smaller footprint and width -Some loss in lift due to canted rotors (%2)

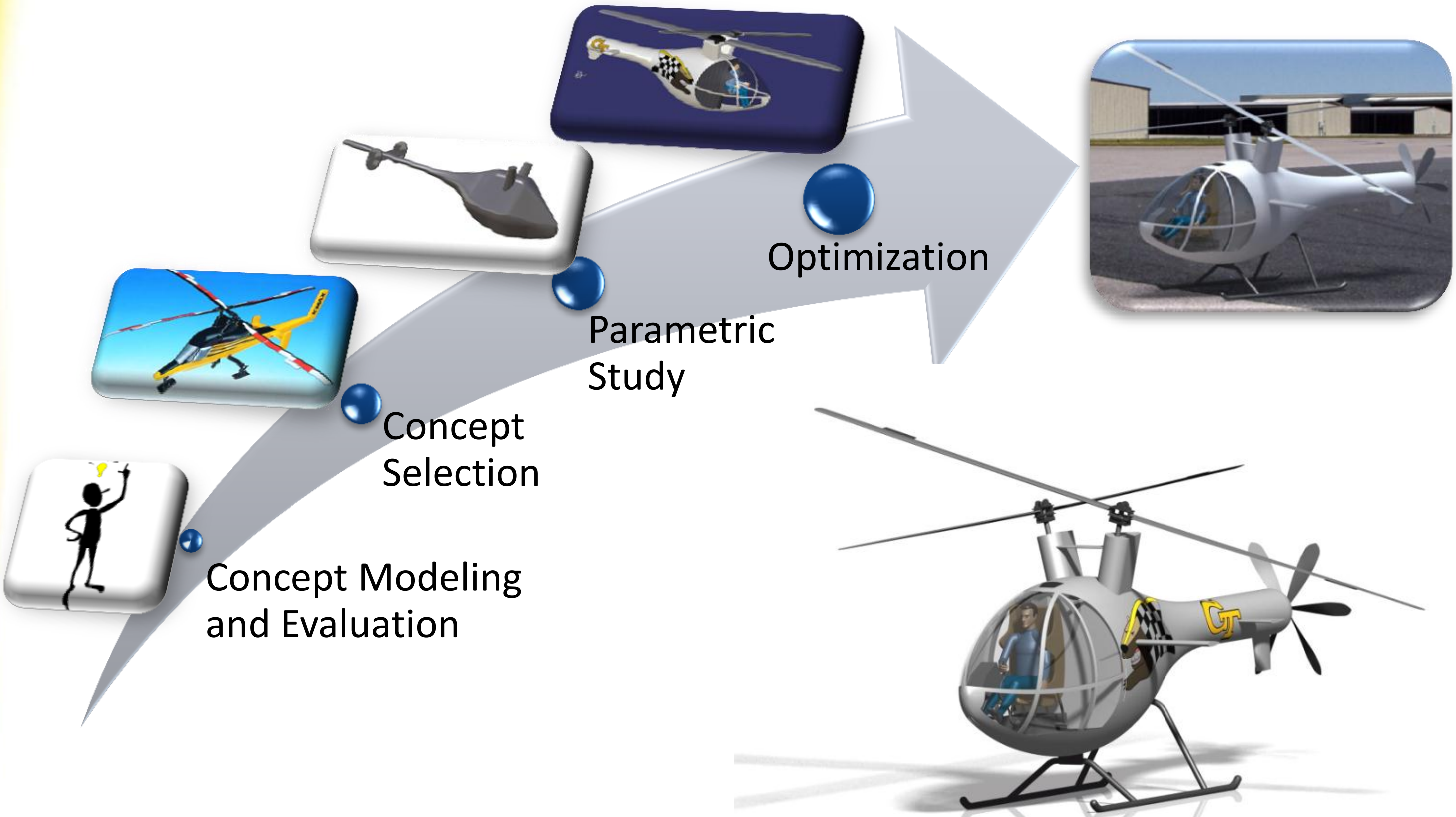
- TOPSIS



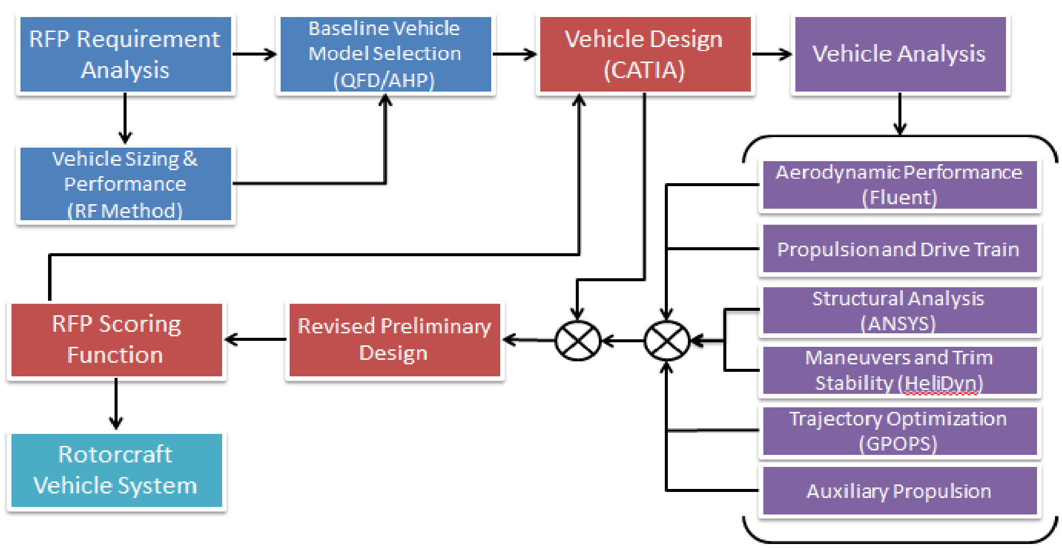


DESIGN SELECTION

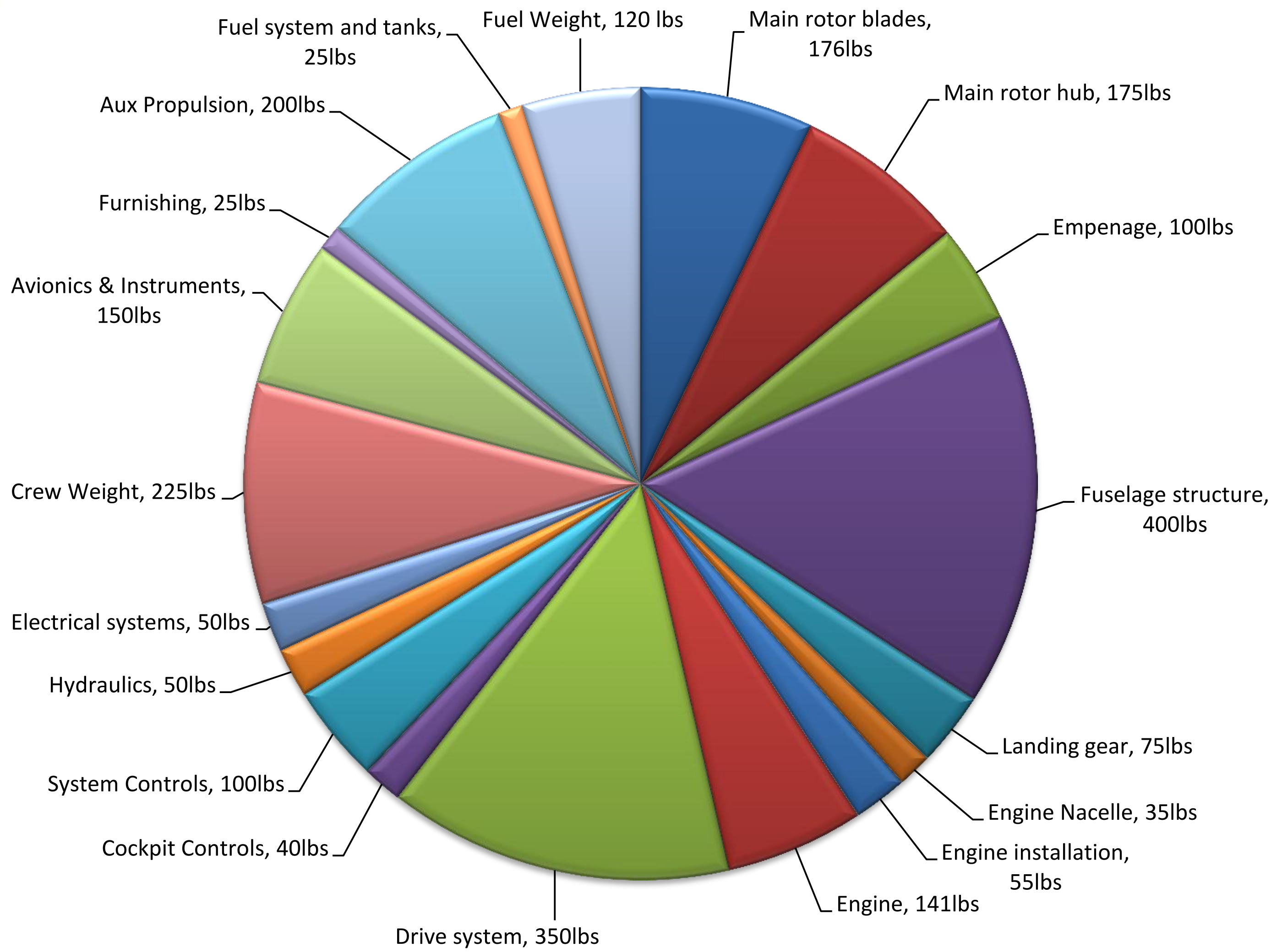
- Design Process Flow map



- Georgia Tech's Integrated Product/Process Development was used during the development of The BADGER



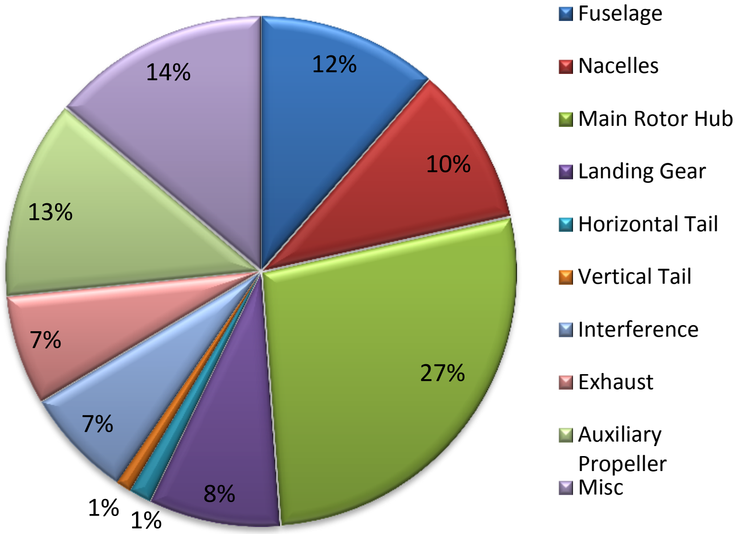
WEIGHT BREAKDOWN



Several trade studies were conducted with respect to material decisions. The primary objective was to effectively choose technologically advanced materials and manufacturing methods that would result in weight reduction while keeping in mind the aircraft's structural integrity, pilot safety and cost effectiveness.

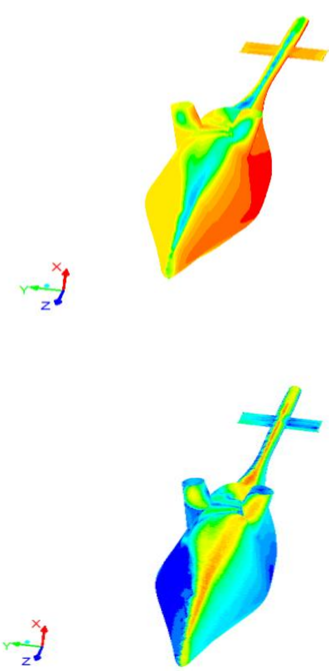
DRAG BUILDUP

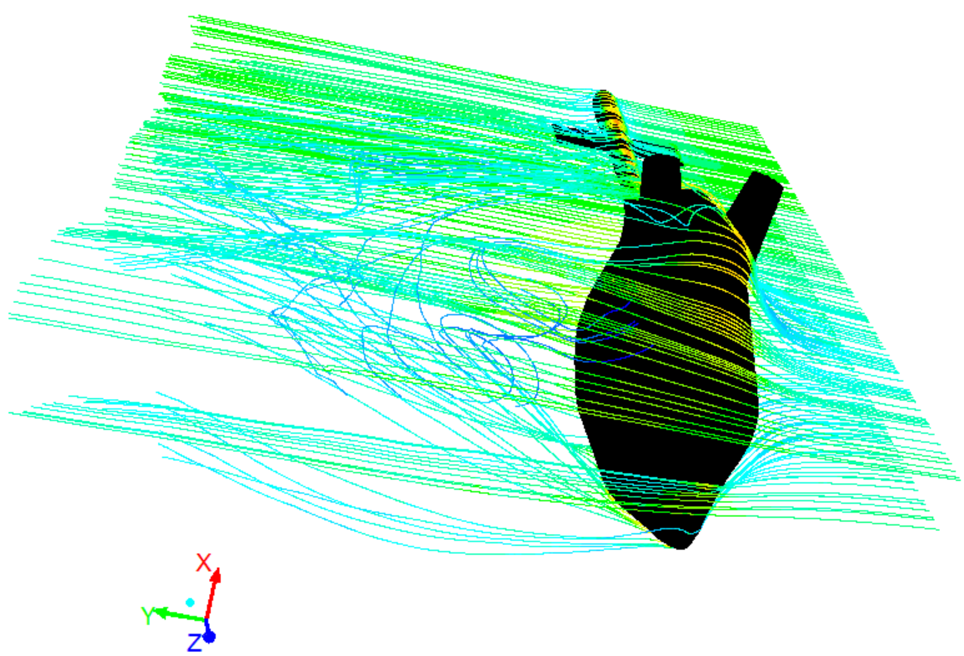
- Empirical drag build-up for forward flight Flat Plate Area (EFPA) of 7.2 ft2



Component	Parasite Drag (ft^2)
Fuselage	0.822
Nacelles	0.7263
Main Rotor Hub	1.9638
Landing Gear	0.6
Horizontal Tail	0.101
Vertical Tail	0.07
Interference	0.5
Exhaust	0.5
Auxiliary Propeller	.912
Miscellaneous	1
Total Frontal	**7.2**

- Computational Fluid Dynamics was used to determine sideward flight Equivalent Flat Plate Area = 41 ft2. This allowed The BADGER team to determine and overcome the thrust required to meet RFP requirement of 60kt sideward flight.



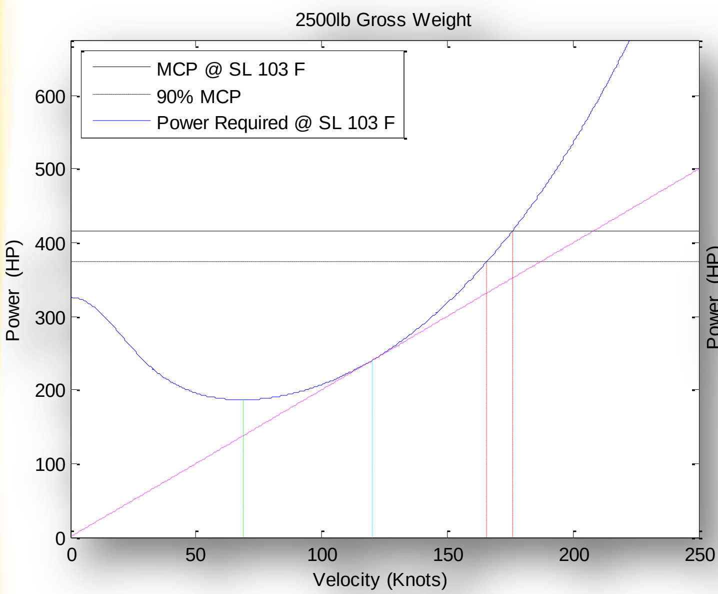


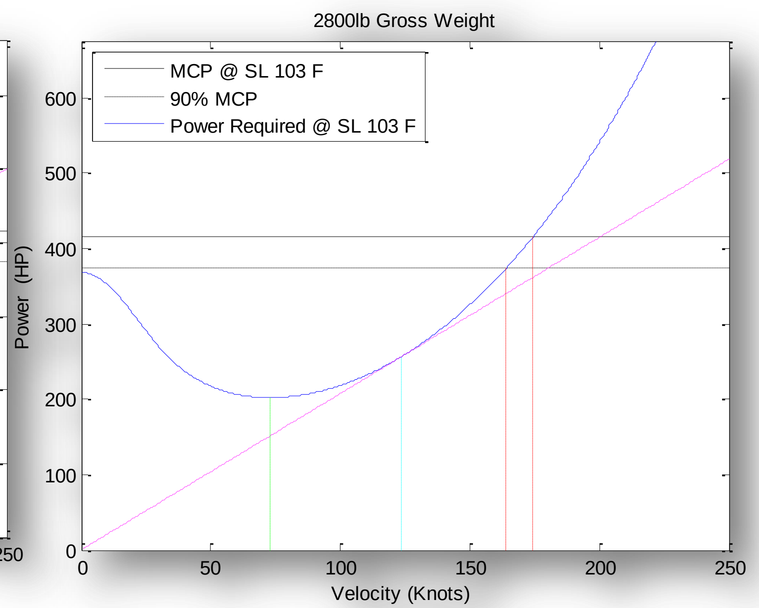
PERFORMANCE ANALYSIS

- Successfully outperforms RFP performance requirements with the use of auxiliary propulsion in the form of a pusher propeller for both increased acceleration and deceleration properties.

Badger Capabilities

- 176 kts max speed @ 103F
- 60 kts sideward flight
- 166 kts max speed at 90% MCP
- Hover at S.L/103° F with and without 300 lbs load

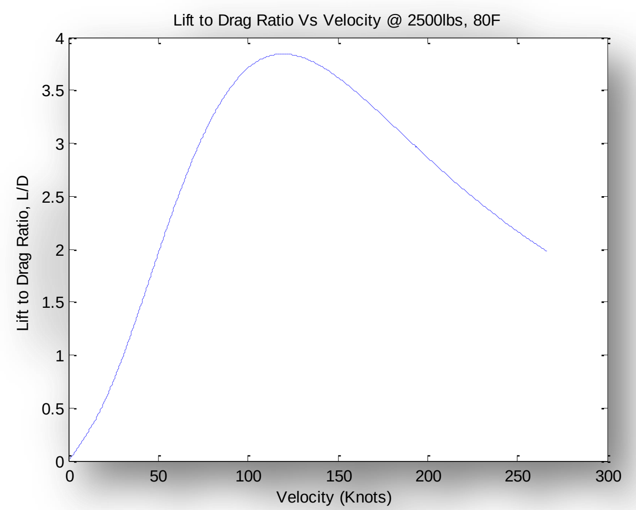


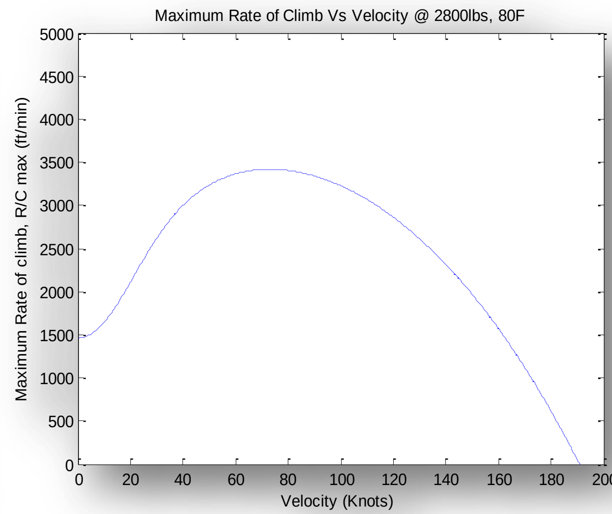


- Sized to a standard atmospheric temperature of 103 degrees Farenheight, The BADGER's performance characteristics allow it not only to perform, but outperform the competition even in demanding weather conditions.

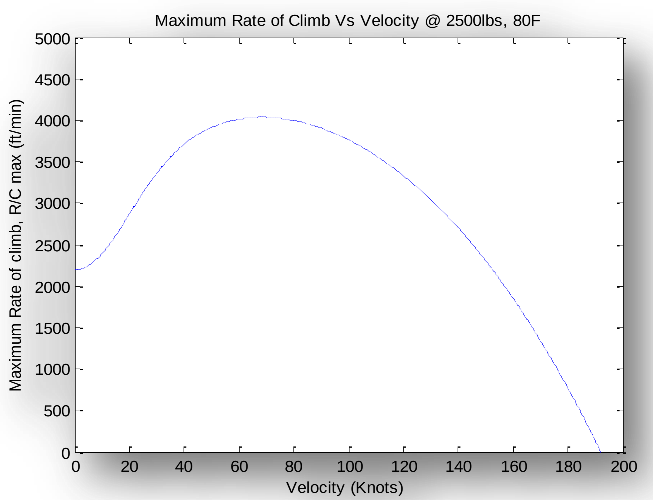
Parameter (103F)	GW = 2500lbs	GW = 2800lbs
Best range speed	119.8312 knots	123.5676 knots
Best endurance speed	68.5893 knots	73.1264 knots
Maximum speed	175.8769 knots	174.2756 knots
Speed at 90% MCP	165.7353knots	164.134knots

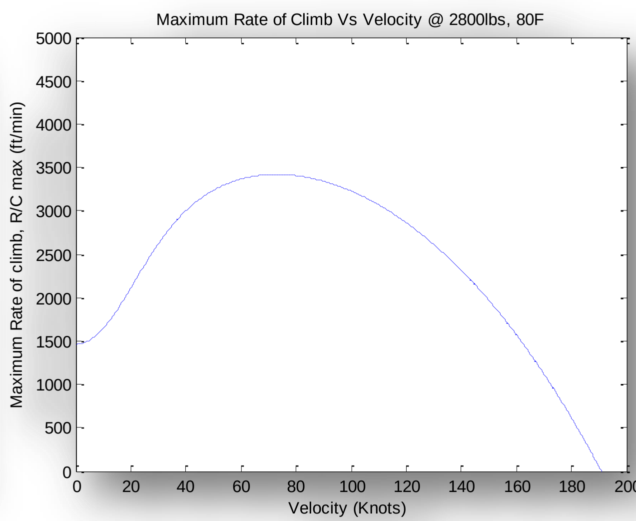
- Outstanding Lift to Drag Ratios



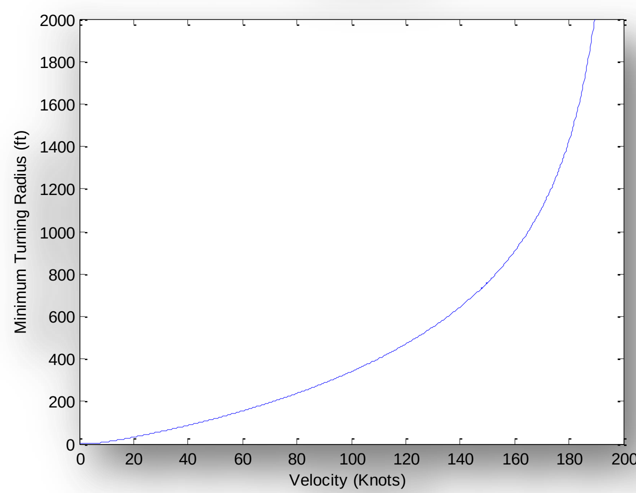


- The BADGER is able to achieve a 4k ft/min maximum rate of climb





- A plot of minimum turning radius versus velocity was necessary to ensure that our helicopter was capable of performing certain maneuvers expected in the race such as the 300 ft 180 degree turn in the beginning of the track.



CONTROLS AND HANDLING QUALITIES

- Nonlinear synchropter model built in HeliDyn
- Controller Design Includes:
  - SAS
  - Attitude Command Attitude Hold
  - Rate Command Attitude Hold
  - Velocity Hold
  - Altitude hold

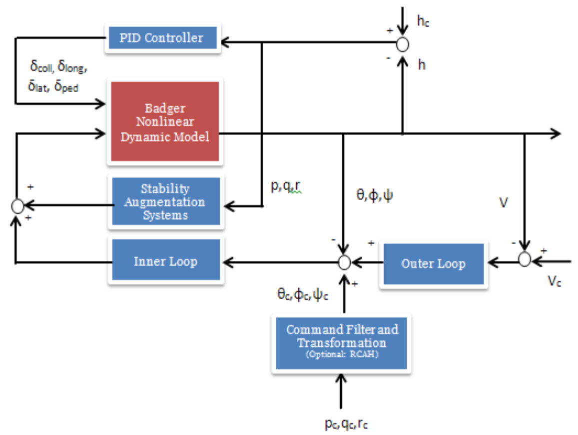
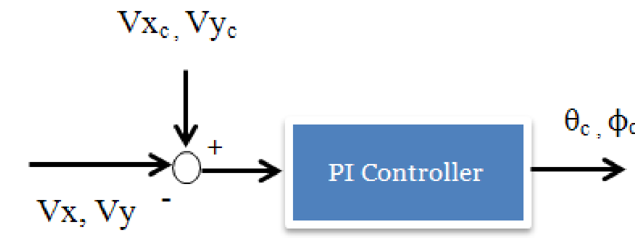
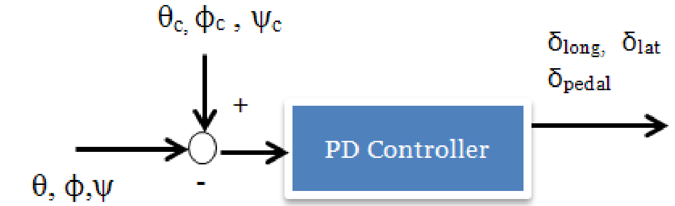


Figure 42: Controller block diagram





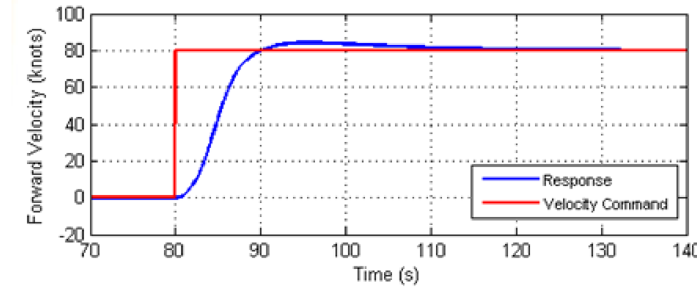


Figure 42 Forward Velocity Command Response

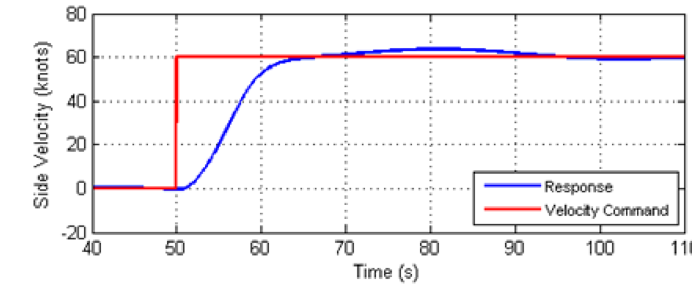
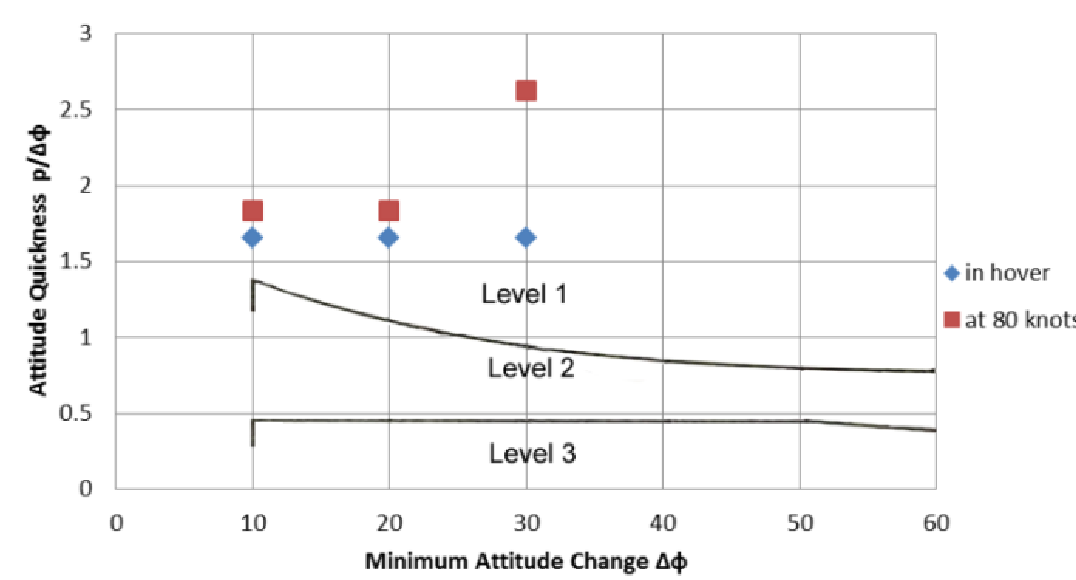


Figure 43 Side Velocity Command Response

- Fly by Light Architecture
  - Replaces mechanical linkages with electronic actuators
  - Reduces weight through use of fiber optic cable
  - Less susceptible to electromagnetic interference than fly by wire systems
  - Electronic actuators allow for easy implementation of a flight control system computer and quick response time which is crucial for a highly maneuverable and agile rotorcraft
- Level 1 Handling Qualities



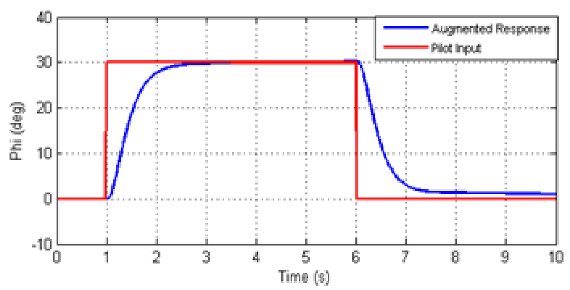


Figure 43 Pilot Roll Input and Augmented Response in Hover using ACAH

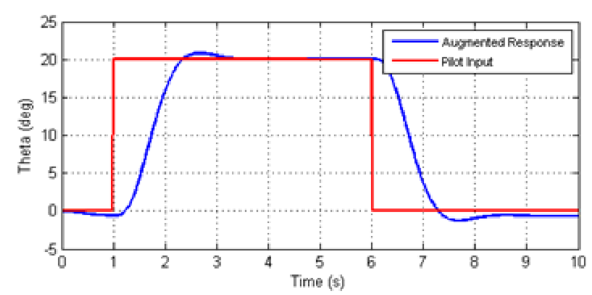


Figure 44 Pilot Pitch Input and Augmented Response in Hover using ACAH

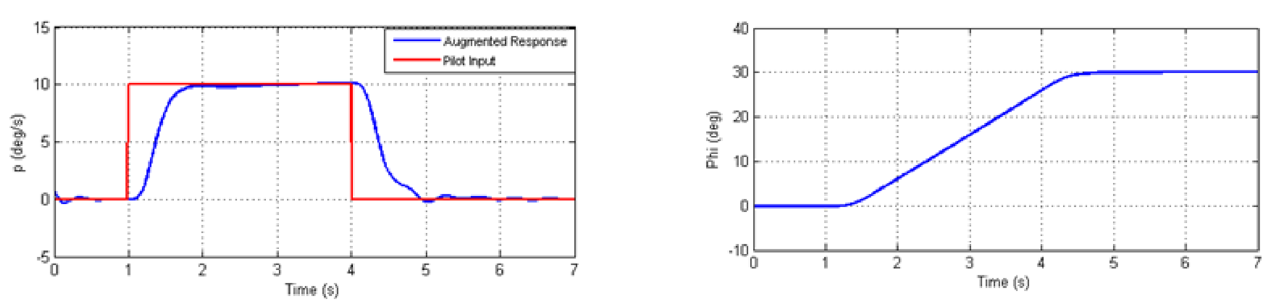


Figure 45 Pilot Roll Step Input, Roll Rate and Roll Angle Response using RCAH at 80 knots

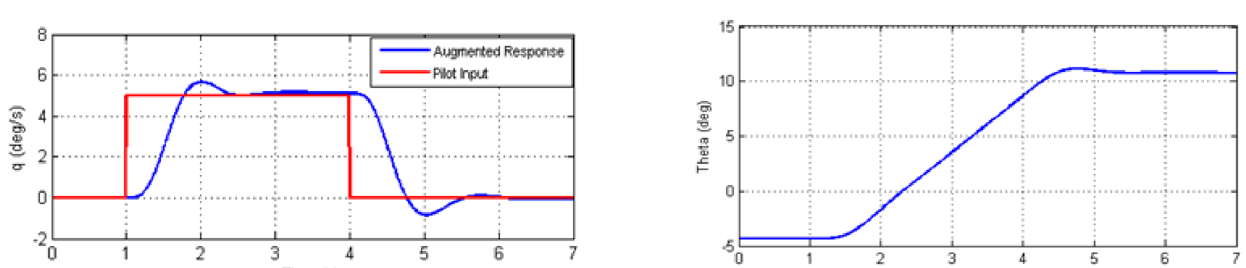


Figure 46 Pilot Pitch Step Input, Pitch Rate and Pitch Angle Response using RCAH at 80 knots

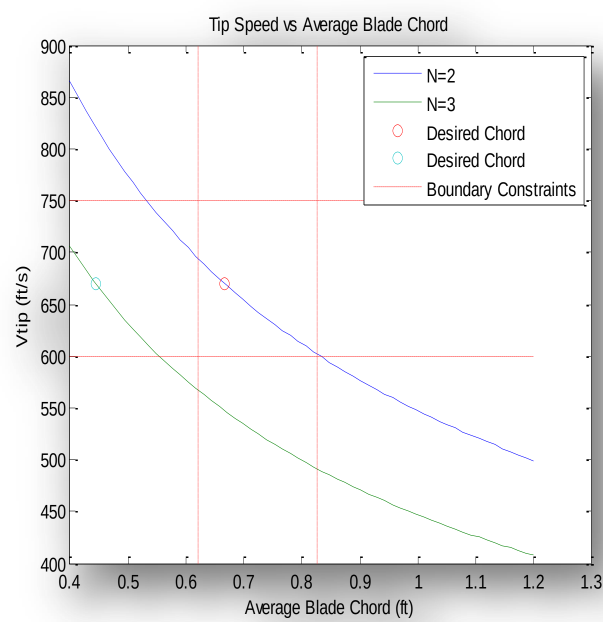
MAIN ROTOR DESIGN

15 ft safety clearance at staging grounds	✓
Minimum of one rotor radius clearance	✓
Clearance through course pylons	✓

Specifications	
Blades per rotor	2
Disk Loading (ft)	2.58
Radius (ft)	12.4
Chord	0.67
Tip speed (ft/s)	670
Aspect ratio,	18.6
Total twist	-10.5°
Root pitch at operating conditions	10.62°
Tip pitch at operating conditions	.125°
Airfoil	VR7B

- Low Disk loading
    - Better maneuverability
    - Limited by RFP size Restrictions

- High Aspect Ratio
    - Decrease in Power Required
    - Structural chord > .05ft

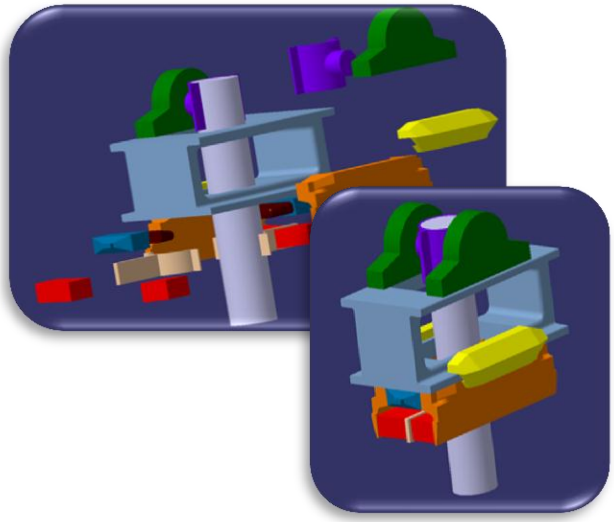


- Highest tip speed possible
    - Increased performance
    - Increased maneuverability
    - Based on VR7b airfoil data

- Blade Element Momentum Theory (BEMT)
    - Used to find optimum airfoil and blade twist

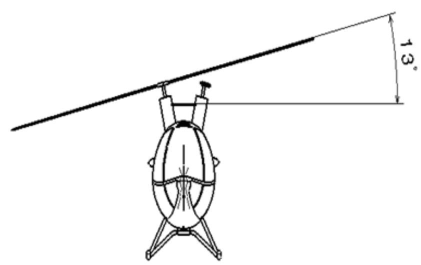
HUB DESIGN

- Teetering hub with hub spring and feathering bearing. Elastomeric hub spring gives control power at <1 G maneuvers

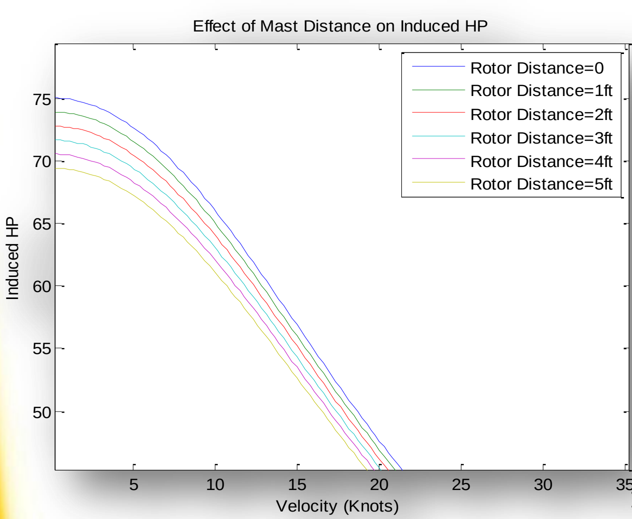


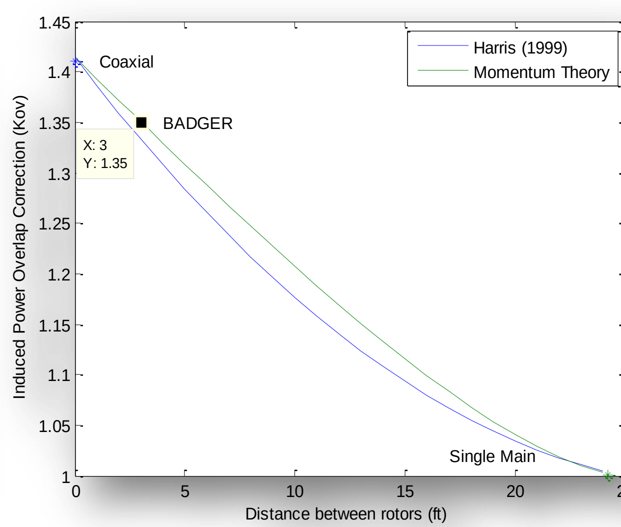
- Servo – flap controls collective and cyclic pitch with the advantage of a lower drag hub by removal of pitch links

- Angle of mast of 13° with 1° precone angle for max flapping angle clearance



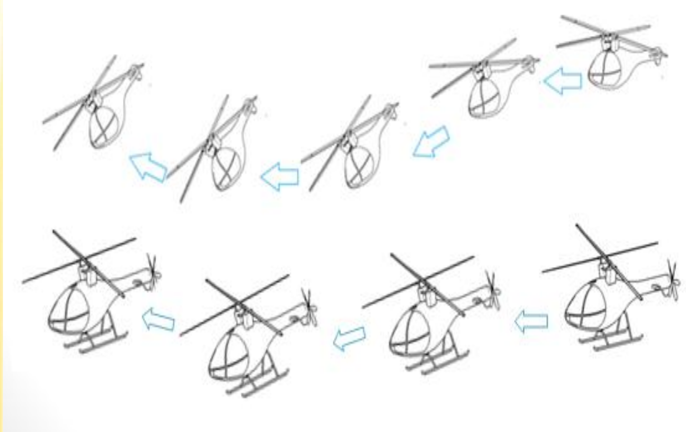
- Ideal mast separation allows Induced Horsepower to be lower than a typical coaxial rotor configuration





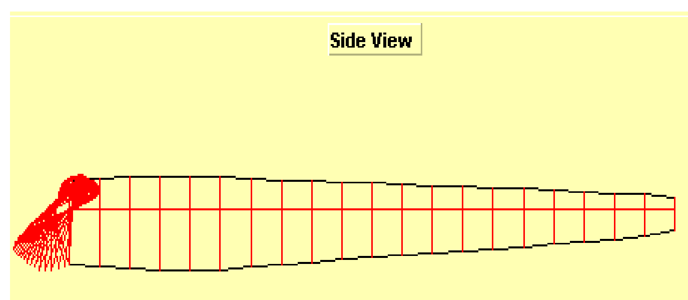
AUXILIARY PROPULSION

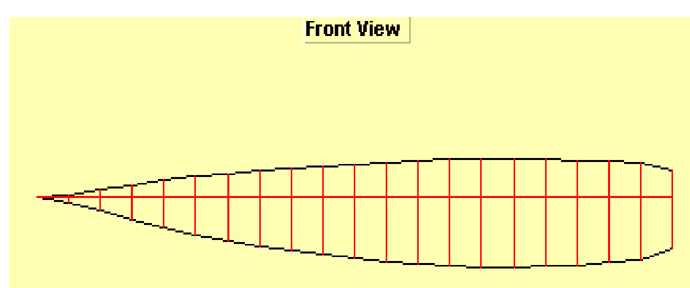
- Used to reduce the effective flat plate drag during accelerations
- Removes tendency of rotor to pitch rearward in forward flight



- Sized to produce enough thrust to counteract 80% of drag at 140 kts forward speed
- Badger incorporates a one sided rotatable horizontal stabilizer to cancel torque produced by aux prop

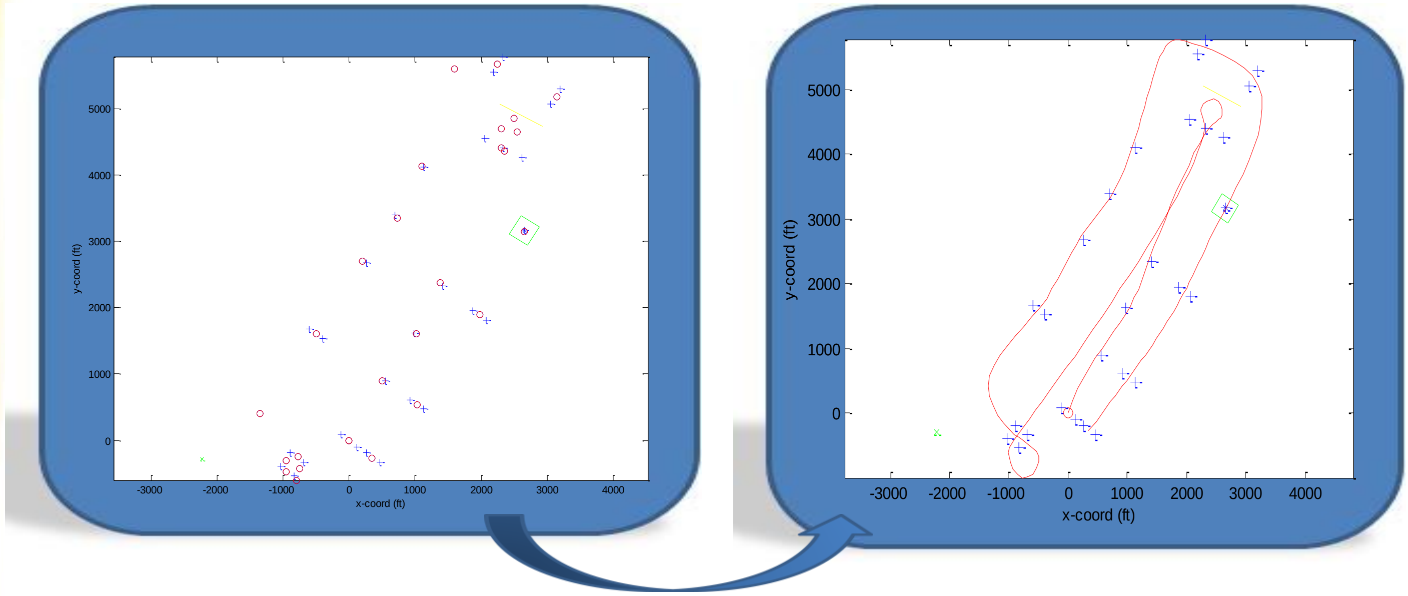
Dimensions	
Diameter	6 ft
Mean Chord	.425 ft
B at .75c	28.1°
Number of Blades	6
Solidity	.271
Airfoils	MH 126 MH 112 MH 116
Performance	
V/nD	1.026
Thrust	511lbs
Power Required (@ 170 knots)	146.4 hp
Efficiency	79%
RPM	2300





TRAJECTORY OPTIMIZATION

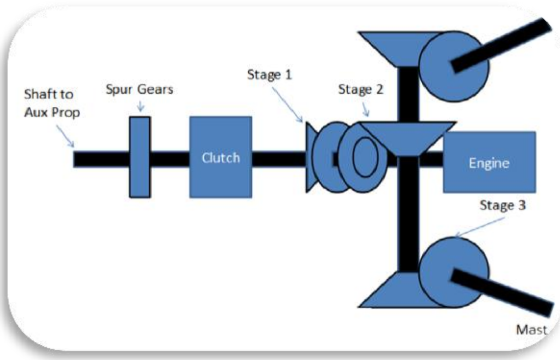
- Optimal control theory combined with human-pilot based constraints
  - GPOPS (General Pseudospectral OPtimal control Software)

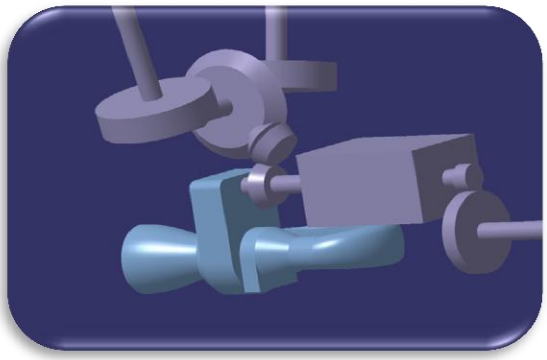


Best time of 4 minutes and 8 seconds

TRANSMISSION DESIGN

- Adequate transmission sizing was performed





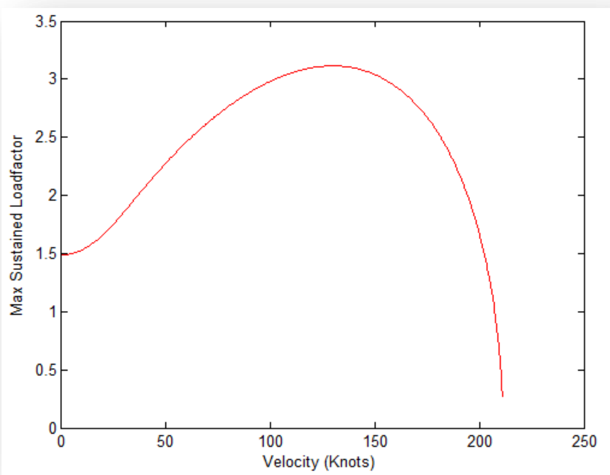
	Stage 1		Stage 2		Stage 3		Aux Spur	
	Pinion	Gear	Pinion	Gear	Pinion	Gear	Pinion	Gear
Diameter (in)	4.65	4.65	4.00	10.64	2.83	11.32	3.00	7.83
Face Width (in)	1.50	1.50	1.50	1.50	2.64	2.64	0.90	0.90
Teeth	20	20	20	53	15	60	15	39

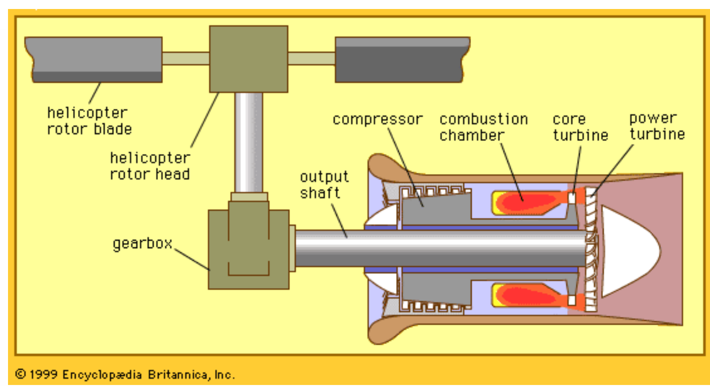
RPM:6000 to 516

ENGINE SIZING

RFP Requirements
125 knots at 90% MCP
Ability to pull a 3g turn (limiting factor)
Ability to fly 60 knots sideways
Must minimize the scoring function by finding the minimum MRP required and minimum fuel consumption
Scaled engine using equations given in RFP

Engine Parameters	
Diameter	11.3 in
Length	24.6 in
Weight	141 lbs





$$Diameter = 2.117 \cdot (MRP_{Unninstalled,SL/ISA})^{0.3704}$$
$$Length = 2.622 \cdot (MRP_{Uninstalled,SL/ISA})^{0.4148}$$

- Appropiate calibrations were performed on The BADGER's engine to comply with RFP regulations and requirements

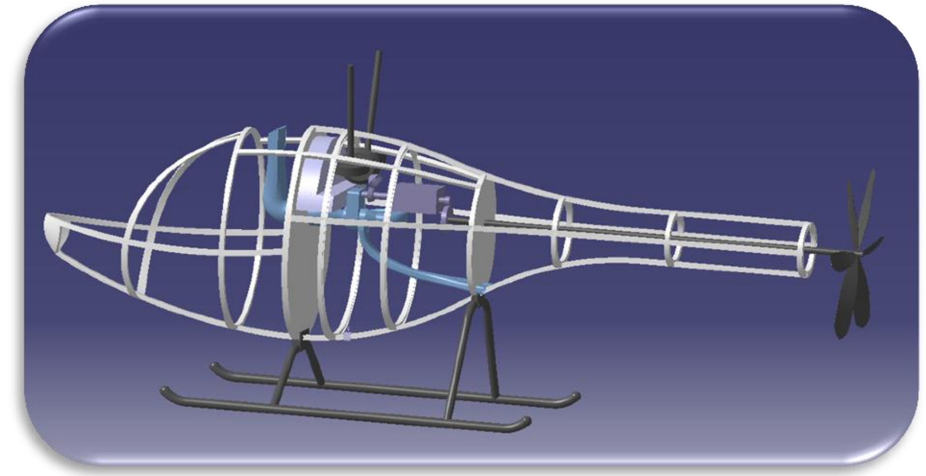
	SL/ISA		SL/103°F		6K/95°F	
	HP	SFC (lb/hp*hr)	HP	SFC (lb/hp*hr)	HP	SFC (lb/hp*hr)
OEI	703.6	0.378	581.5	0.392	474.2	0.390
MRP	672.1	0.379	550.0	0.396	445.4	0.395
IRP	626.5	0.384	508.4	0.403	409.8	0.402
MCP	512.4	0.398	415.2	0.424	338.0	0.422
Part Power	336.0	0.448	275.0	0.490	222.7	0.486
Idle	134.1	0.706	110.0	0.824	89.2	0.816

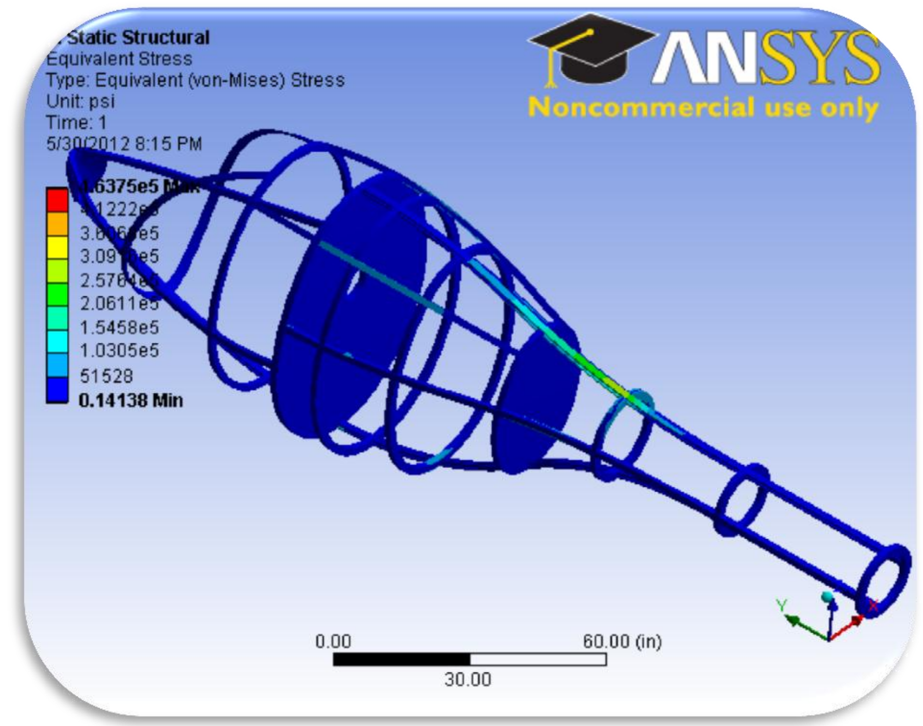
STRUCTURAL AND INTERNAL LAYOUT

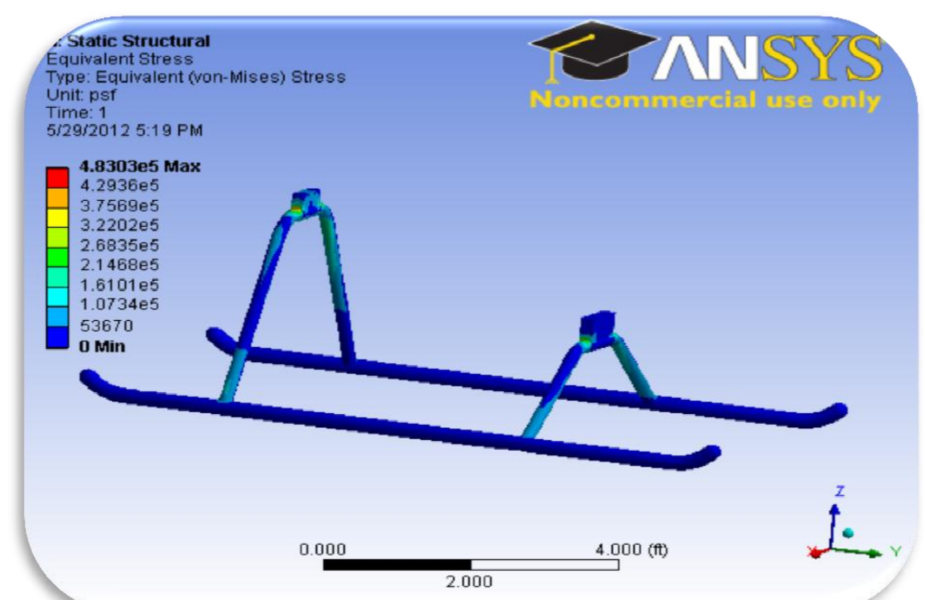
- Lightweight aluminum airframe composed of I beams, box beams, and solid beams
- Two primary bulkheads to carry crash loads and main aerodynamic loads
- Nose plate used to connect bottom I beam two side box beam longerons

- Advantageously placed internal systems to maintain a center of gravity along the auxillary propulsion thrust vector
- Internal systems attached to upper I beam and longerons as well as front bulkhead to optimize load paths
- Load hook mounted on the bottom I beam to support 300 lb slung load

- Aluminum hollow tube crashworthy landing gear
- FEA landing gear and airframe test conductued using ANSYS static strucural toolbox
- Crash loads approximated with a 2g load factor on landing gear supports and 4g on airframe





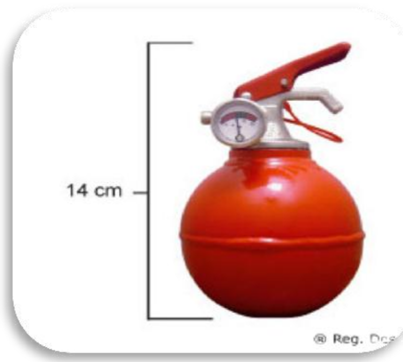


SAFETY CAPABILITIES

- 5 Point harness BAE S7000 crashworthy seat that meets MIL – 58095A and MIL – STD -810 safety requirements

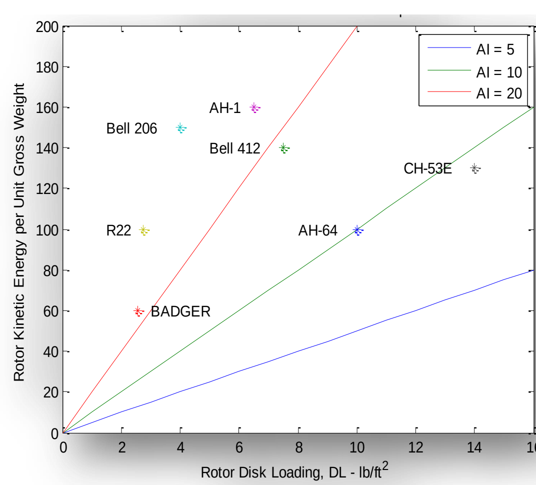
- Phantom 5 minute emergency oxygen tank allowing pilot to survive underwater while emergency personnel perform rescue mission

- Portable and compact fire extinguisher that allows The BADGER to comply with the requirements given by the 2012 RFP regarding fire protection



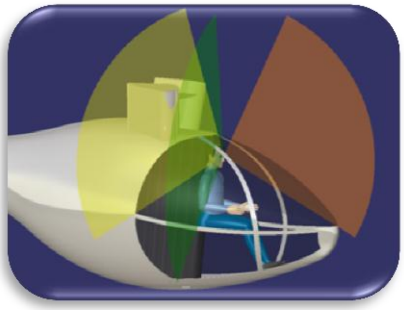
- Small and light weight military designed inflatable raft which allows The BADGER to comply with the requirements given by the 2012 RFP regarding flotation for the pilot

- Autorotative index of 22.5 for the unfortunate case of an engine failure during the race



COCKPIT DESIGN

- High-visibility cockpit design based on Marenco Swisshelicopter concept. Planes of vision meet MILSTD-850B requirements



- Heads-Up Display (HUD) projecting optimized trajectory course onto windshield for pilot aid during race

- Dynon Skyview 7" Electronic Flight Instrumentation System (EFIS)
- Contains Primary Function Display (PFD), Moving Map, and Engine Monitoring
- Installed with "soft stop" alerting system (EICAS) to alert pilot in event of critical engine levels or approaching any helicopter limits

- Quick release switch for cargo hook in case of an unexpected emergency landging is required

TOP TEN TRADE STUDIES

1. Intermeshing vs. Other Configurations
2. Auxiliary Yaw control
3. Auxiliary Forward propulsion
4. Hub Configuration
5. Main Rotor and Airfoil selection
6. Mast Separation
7. Transmission Selection
8. Electric Propulsion
9. Material Selection
10. Cockpit Technologies

- Based off of the trade study results, all technologies used are currently on the market
- The Badger is a TRL of 7.5, this places it in "The System Development phase"
- Five Year Expected Production

COST ANALYSIS

Synchropter

Total Burdened Cost for Average of 1 Aircraft, 2001$

Previous Screen

	Total Average Cost by System			
	Labor	Material	Subcontract	Total
Wing	$0	$0	$0	$0
	$0	$0	$0	$0

Rotor
Hub
Blade
Tail
Vertical Stabilizer
Horizontal Stabilize
Tailrotor
Fuselage
Basic Structure
Windows
Crew Doors
Passenger Doors
Baggage Door
Compartment Door
Floor
Tailboom
Pylon Support
Landing Gear
Landing Gear
Tail Skid
Nacelles
Firewall
Cowling
Engine Mounts

Nacelles	$123,044	$29,889	$1,079	$154,012
Firewall	$36,801	$9,050	$759	$46,610
Cowling	79,502	15,091	163	94,755
Engine Mounts	6,741	5,748	157	12,647

Air Induction
Air Inlet
Inlet Particle Separator
Powerplant
Engine
Engine Installation
Ejector
Tailpipe
Engine Controls
Engine Start System
Engine Wash
Lubrication System
Fuel System
Drive System
Main Transmission and Ma
Tailrotor Gearbox
Freewheeling Unit
Engine Input Shaft
Tailrotor Driveshaft
Flight Controls

Flight Controls	$5,130	$42,150	$34,812	$82,091
Cockpit controls	$0	$10,639	$4,435	$15,075
Non-rotating controls	0	13,491	1,731	15,221
Rotating controls - main rotor	1,938	16,956	2,417	21,311
Rotating controls - tail rotor	3,192	1,064	1,263	5,518
Rotor hydraulic actuators	0	0	24,966	24,966
Auxililary Power Unit	$1,863	$75	$155,369	$157,307
Instruments	$4,075	$228	$35,501	$39,803
Hydraulics	$1,342	$1,009	$13,213	$15,564
Electrical	$38,962	$20,905	$24,818	$84,685
Avionics	$8,270	$792	$21,243	$30,305
Furnishings and Equipment	$0	$12,092	$7,209	$19,302
Crew Seats	$0	$3,254	$2,969	$6,223
Passenger Seats	0	0	1,184	1,184
Fire Extinguishing	0	1,764	1,105	2,869
Soundproofing	0	0	1,685	1,685
Miscellaneous Furnishings	0	7,075	267	7,341
Air Conditioning	$1,562	$3,813	$1,567	$6,942
Bleed air, heat, and defog	$1,562	$3,813	$1,567	$6,942
	$0	$0	$0	$0
Load and Handling	$0	$3,817	$0	$3,817
Final Assembly	$133,068	$0	$0	$133,068
Subtotals	$535,611	$426,190	$728,124	$1,689,926
Total Average Production Cost				$1,689,926

Engineering	
Design	$24,410,000
Flight Test	$3,251,000
Component Test	$10,387,000
Systems Engineering/Project Management	$3,173,000
Total Engineering	$41,221,000
Manufacturing Engineering	
Planning, Loft, Other	$7,315,000
Project Management	$611,000
Total Manufacturing Engineering	$7,926,000
Tooling	
Tool make	$9,245,000
Outside Tooling	$5,403,000
Total Tooling	$14,648,000
Manufacturing	
Prototype	$2,496,000
No GTV, STA, or FTA Required	$0
Flight Test	$2,197,000
Component Test	$8,790,000
Total Manufacturing	$13,483,000
Logistics	$224,000
Other	
Travel and Per Diem	$941,000
Direct Expense	$4,838,000
Total Other	$5,779,000
Total Program	$83,281,000

- Average production cost per helicopter: **$1,689,926**

GT BADGER

GT BADGER

GT – BADGER : WE'LL SEE YOU AT THE RACE LINE

- The BADGER's official η = 1380.6
- All RFP requirements are 100% satisfied
- The BADGER is a highly maneuverable unconventional agile rotorcraft
- Its unique intermeshing rotor configuration separates it from conventional designs
- The auxiliary propulsion system allows for incredible acceleration and deceleration during the race

RFP Requirements	The Badger
Capability to perform all mission segments	✓
Hover at S.L/103° F	✓
125 kts at 90% MCP	✓
60 kts translational flight at S.L/103°F	✓
15 ft safety clearance at staging grounds	✓
Fuel reserve of 15 minute flight at V_{BR} and TOGW	✓
MIL STD-850B Vision requirements	✓
Avionics suite in according to FAA requirements in NY VFR corridor	✓
Contains floatation and fire protection for pilot	✓

GT BADGER

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MIDDLE EAST TECHNICAL UNIVERSITY