

# ***Kestrel***

***Transition into a new era***

**EXECUTIVE SUMMARY**

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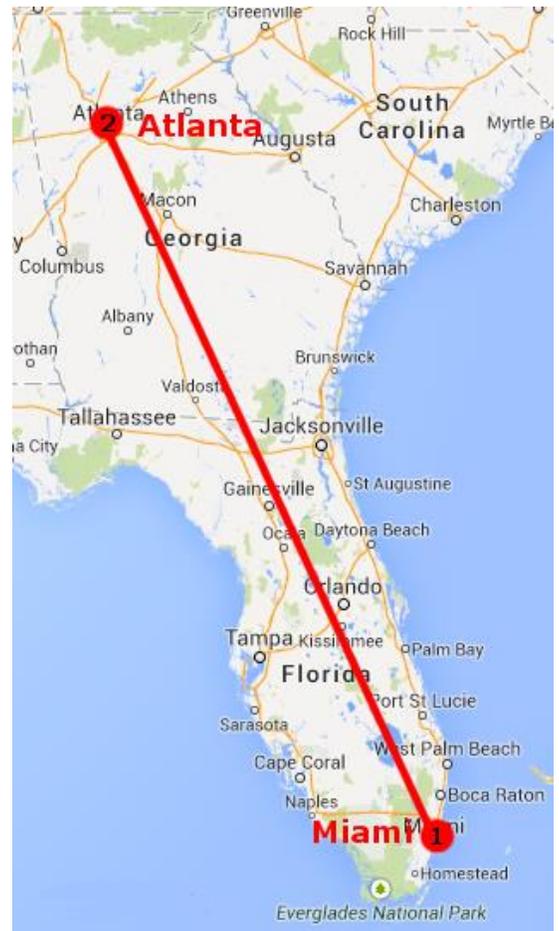
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# Introduction

Consider a situation where an unknown chemical agent is released in a densely populated metropolitan area, such as Miami, FL (① on map). The Centers for Disease Control (CDC) in Atlanta, GA (② on map) calls upon the Georgia Army National Guard to request a UH-60 Blackhawk to airlift a group of scientists using chemical sensing and processing equipment. The scientists are then ferried out to Miami where samples of the air are taken.

In response, the Guard could instead send their newly acquired *Kestrel*. With a top airspeed of 350 KTAS it travels the nearly 600 nautical miles distance from the CDC headquarters to Ground Zero in approximately one hour and 45 minutes; two hours earlier than the UH-60 would have arrived. The *Kestrel* could utilize its VTOL capabilities by landing in restricted spaces, such as on top of buildings, in parking lots, and at roadway intersections, while collecting and processing air samples. The results are sent via a satellite communications uplink to the CDC for an on-the-fly processing of data where the composition of the aerosol is determined. In this situation, lives could be saved because of the quick response capabilities and increased performance margins of the *Kestrel* compared to current rotorcraft fleet.

The *Kestrel* unmanned tailsitter rotorcraft was designed by the University of Maryland's graduate team in response to the 2014 American Helicopter Society's Student Design Competition, sponsored by AgustaWestland. The *Kestrel*'s hybrid rotorcraft design achieves fixed-wing-like speed and range capabilities, along with the vertical takeoff and landing (VTOL) capabilities of a traditional helicopter. This aircraft configuration, combined with a novel dual-speed gearbox, allows the *Kestrel* to achieve remarkable cruise and hover efficiencies and a top airspeed of 350 KTAS, 95 KTAS faster than any previous rotary-winged VTOL aircraft.



The *Kestrel*'s mechanically simple design utilizes the same propulsion system for hover and forward flight to give a low empty weight. Autonomous and remote piloting capabilities ensure complex maneuvers, such as transitioning flight modes and landing at unprepared locations, are safe and successful. Combining all of these design features into a single platform, the *Kestrel* represents the transformation of VTOL aircraft performance into a new era.



***Kestrel*: Transition Into a New Era**

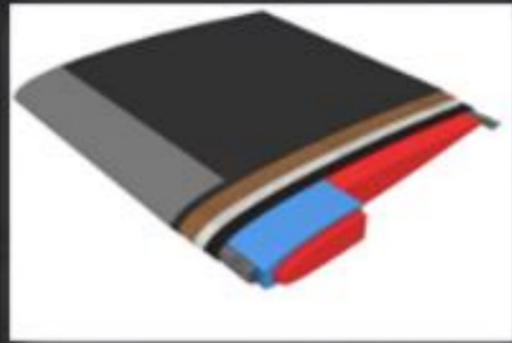
Fully Autonomous  
and Remote Pilot  
Capabilities



*Vestrrel*



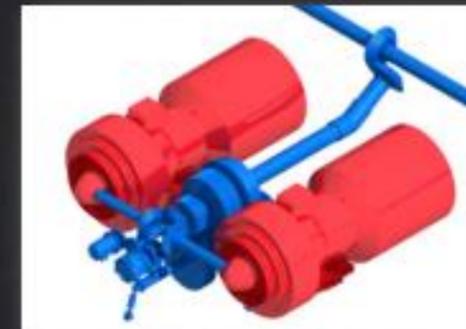
All-Moving Canard



Composite  
Rotor Blades



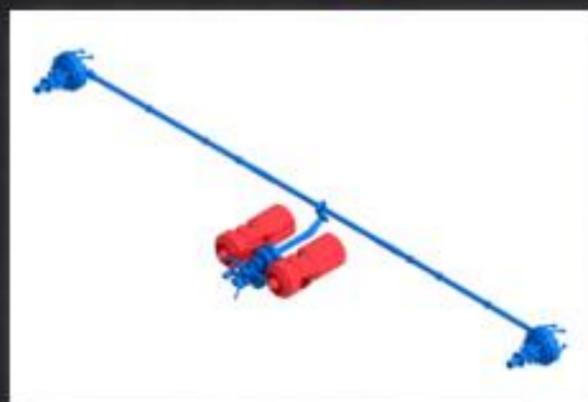
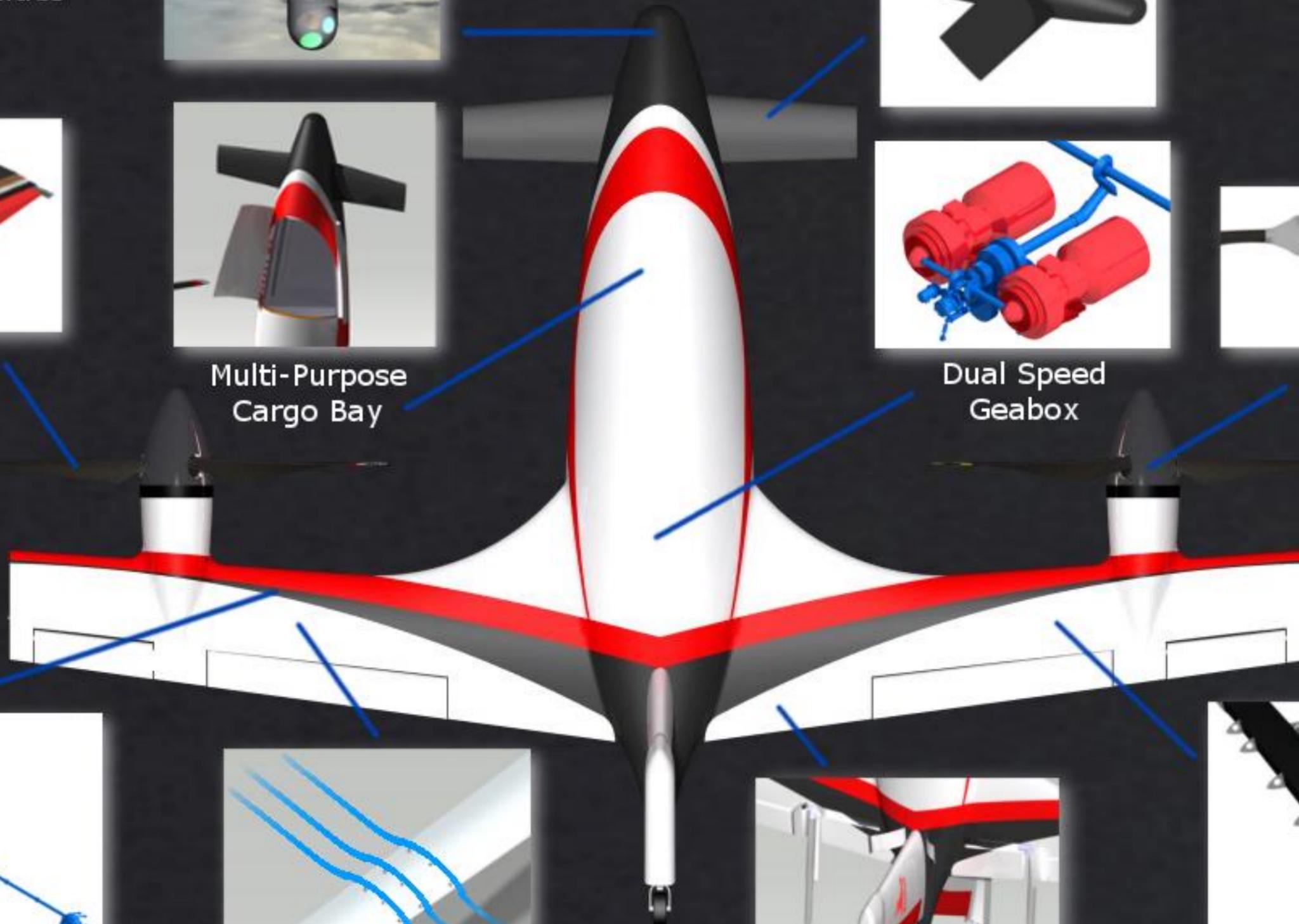
Multi-Purpose  
Cargo Bay



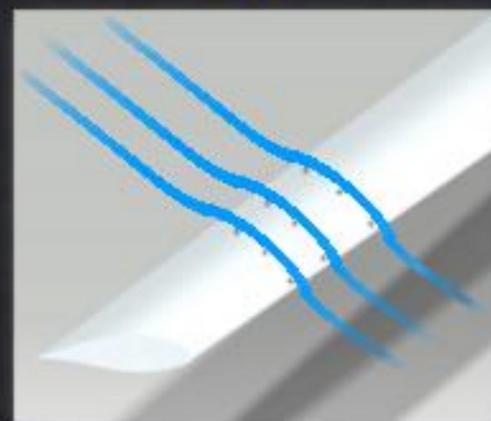
Dual Speed  
Geabox



Stiff In-Plane  
Proprotor Hub



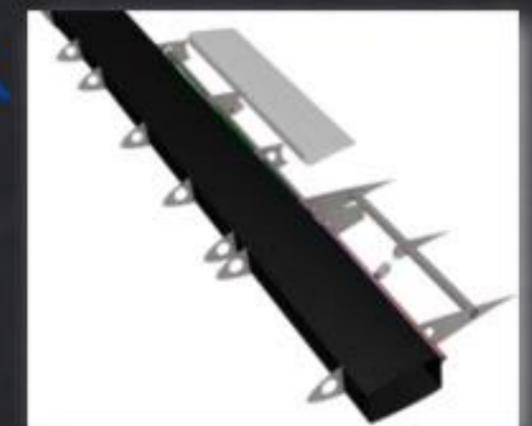
Cross-Shafted Rotors



Stall Detection  
Pressure Sensors



Retractable Wing  
Landing Gear



Composite Torque  
Box with Integral  
Fuel Tanks

# Request for Proposal

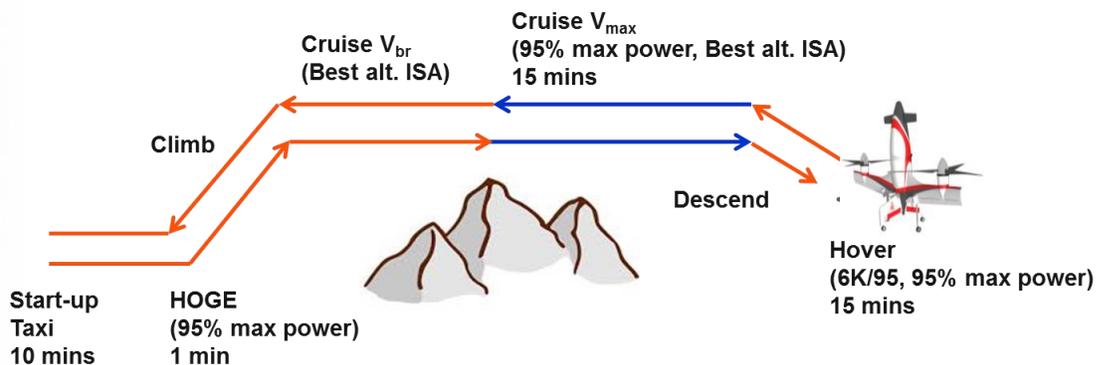
The Request for Proposal (RFP) shared the requirements set by the United States Defense Advanced Research Projects Agency (DARPA) for its X-Plane program. DARPA solicited proposals to design and develop a high performance VTOL technology demonstrator aircraft. Such an aircraft would perform at a level representative of a significant jump past the boundaries encountered by today's VTOL aircraft.

Current VTOL designs are the result of unsatisfactory compromises between airspeed, endurance, payload capabilities, and efficiency. DARPA presents a challenge to the aerospace industry to break from traditional aircraft configurations and to design radically new air vehicle configurations and subsystem technologies that can expand the capabilities of operational VTOL aircraft.

In the spirit of DARPA's X-Plane program, the AHS RFP requires the following:

- Sustained top airspeed of between 300 KTAS and 400 KTAS
- At least 75% hover power loading efficiency
- A vehicle lift-to-drag ratio of at least 10
- Useful load capability of at least 40% of the gross vehicle weight
- Payload capability of at least 12.5% of the gross vehicle weight
- Integrate only existing engine technology
- Subsystems must be mature in 52 months

Furthermore, all design entries are judged with reference to a standardized flight profile, which combines multiple best range cruise segments, maximum airspeed cruise segments, and a mid-mission hover segment. The designers have the latitude to determine the maximum cruise airspeed, cruising range, and operating altitude.



**Kestrel: Transition Into a New Era**

# The New State of the Art

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The *Kestrel* is a unique tailsitter vehicle configuration that is comprised of a main fixed-wing and forward canard. Two large open rotors near each wing tip each use collective and cyclic pitch controls similar to a traditional helicopter rotor. At rest, the *Kestrel* perches on two fixed landing gear integrated into the vertical tails and two retractable landing gears mounted in the main wing. An aftward center of gravity provides vehicle stability in hover and a forward canard augments vehicle stability in forward flight. Control in hover is provided by cyclic and collective rotor controls, while in forward flight, the various vehicle controls are provided by the canard, main wing ailerons, and tail rudders.

The tailsitter configuration was first designed and flown in the 1950s. These vehicles were manned and pilots had great difficulty when landing because of the unfavorable seating orientation. With the advent of unmanned vehicle technologies, the strengths of the tailsitter platform over conventional rotorcraft designs are no longer limited by the seat orientation.

The unmanned tailsitter configuration was selected by the design team because it presents distinct advantages over other configurations such as the single main rotor, tiltrotor, fan-in-wing, coaxial, and compound. The *Kestrel* exhibits a high top airspeed because of the aerodynamically clean fuselage and fixed-wing like fuselage-wing-rotor layout which reduce parasitic drag. The *Kestrel*'s high installed power not only gives it high top airspeed capabilities, but also the ability to hover at 6K/95F (approximately 10,000 ft ISA density altitude), increasing the *Kestrel*'s accessible areas of operation to hot and high conditions, that have been required in recent conflicts. The *Kestrel* also has longer range and endurance capabilities over similarly sized tiltrotors and helicopters, increasing its area of operations.

The mechanically simple design gives the *Kestrel* a 57% empty weight fraction, lower than most tiltrotors of today. This empty weight fraction is achieved by utilizing a single propulsion system for hover and forward flight, unlike most compound rotorcraft configurations. Weight is also decreased by the use of composites for several subsystems on the aircraft, which includes a wing torque box stiff enough to prevent whirl flutter while allowing for a high aspect ratio wing to maintain forward flight efficiency. A novel dual-speed gearbox design allows the *Kestrel*'s rotors to maintain high propulsive efficiency during both low-speed cruising flight as well as in high-speed flight. This efficiency significantly increases the *Kestrel*'s range capabilities.

***Kestrel*: Transition Into a New Era**

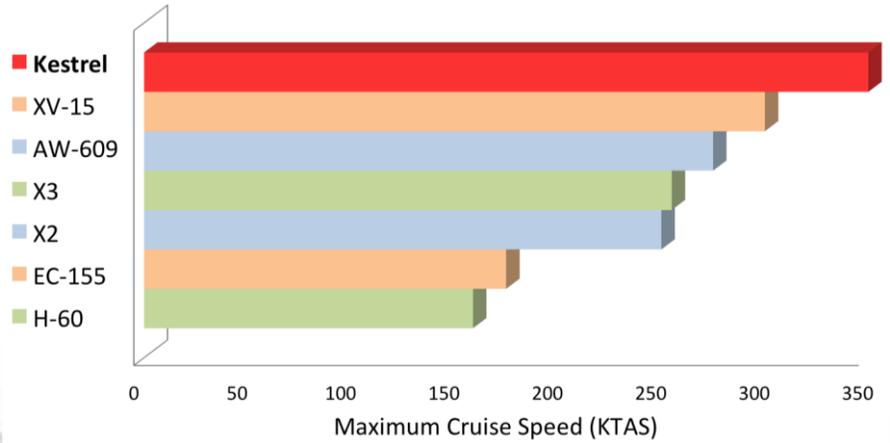
The *Kestrel* is a highly automated aircraft that ensures safety, reliability, and also reduces pilot workload. The advanced avionics suite and flight control system can pilot the *Kestrel* autonomously. Triple redundancy of communications and navigation equipment safeguard the aircraft from system failure and can guide the vehicle in challenging terrain. However, if so desired, the *Kestrel* can be remotely piloted from a mobile ground control station. The extensive array of onboard sensors allow the pilot to proficiently control and monitor the aircraft. The flight controllers automate the task of landing on rough and unprepared surfaces as well as the highly complex maneuvers of transitioning to and from airplane and helicopter modes. All of these features significantly reduce the pilot's workload and reduce the probability of failure.

The *Kestrel* is an affordable aircraft because of it has a relatively low capital operating cost. It utilizes the Turbomeca RTM322 01/9 engine, which has been in production for 16 years and is installed on several aircraft operating in the current fleet. The *Kestrel* takes advantage of the reliability and maintenance record of this engine by requiring only minor modifications to the oiling system to operate in a vertical orientation. This proven engine feature significantly reduces the design and development costs of the power unit. Overall, the *Kestrel* only costs marginally more than an EC155, a single main rotor helicopter which is in a similar weight class. However, the *Kestrel* is a cost efficient design because its performance exceeds the EC155 in top airspeed, hover ceiling, range, and endurance.

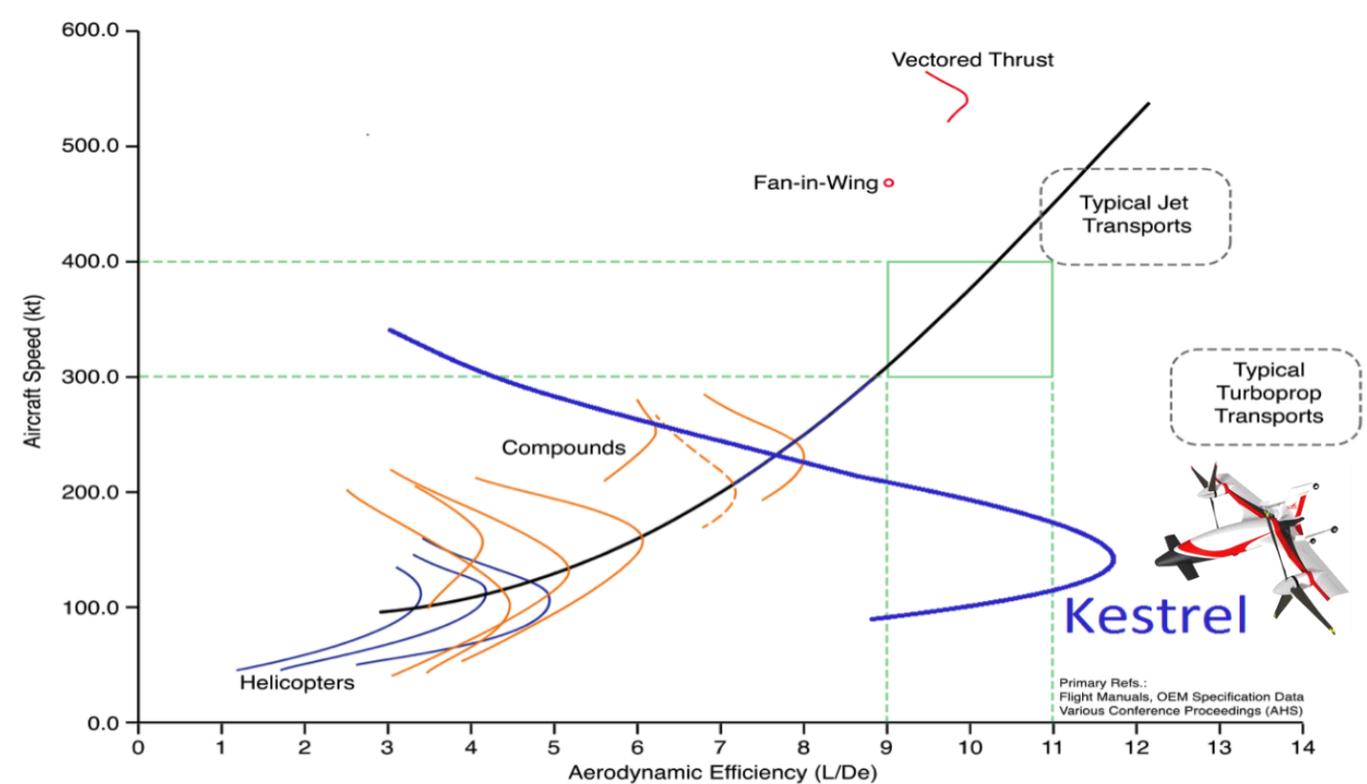
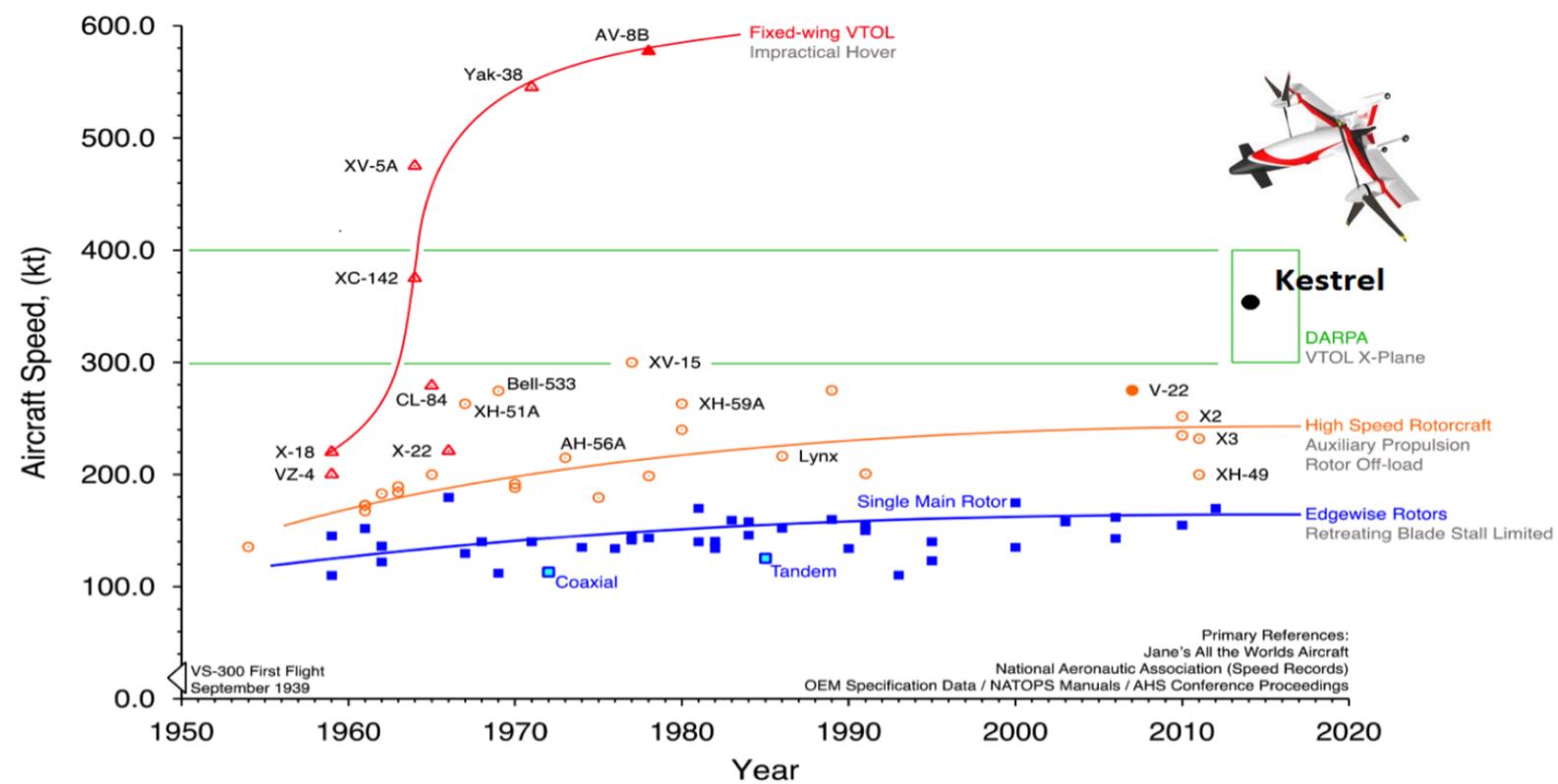
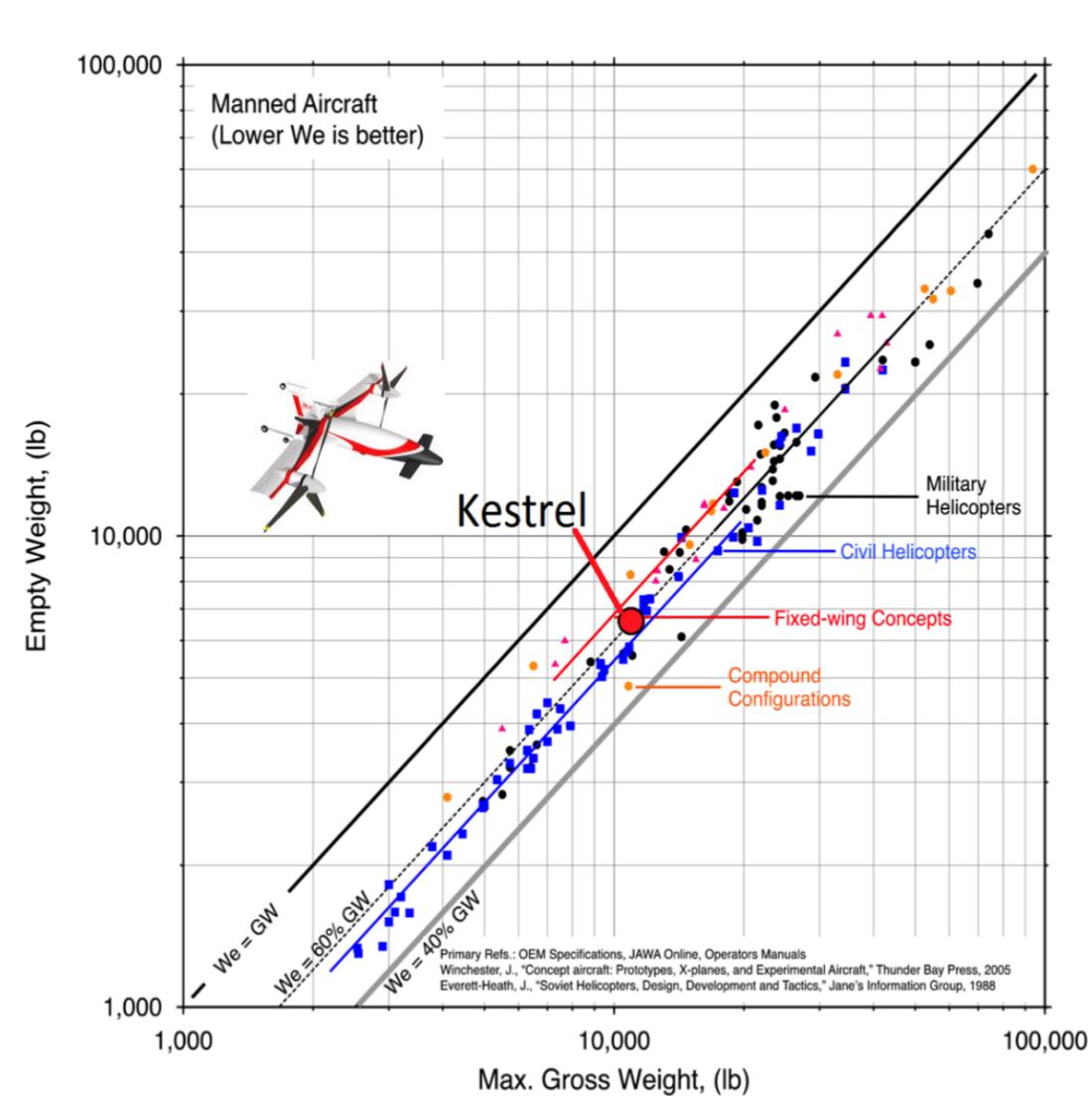
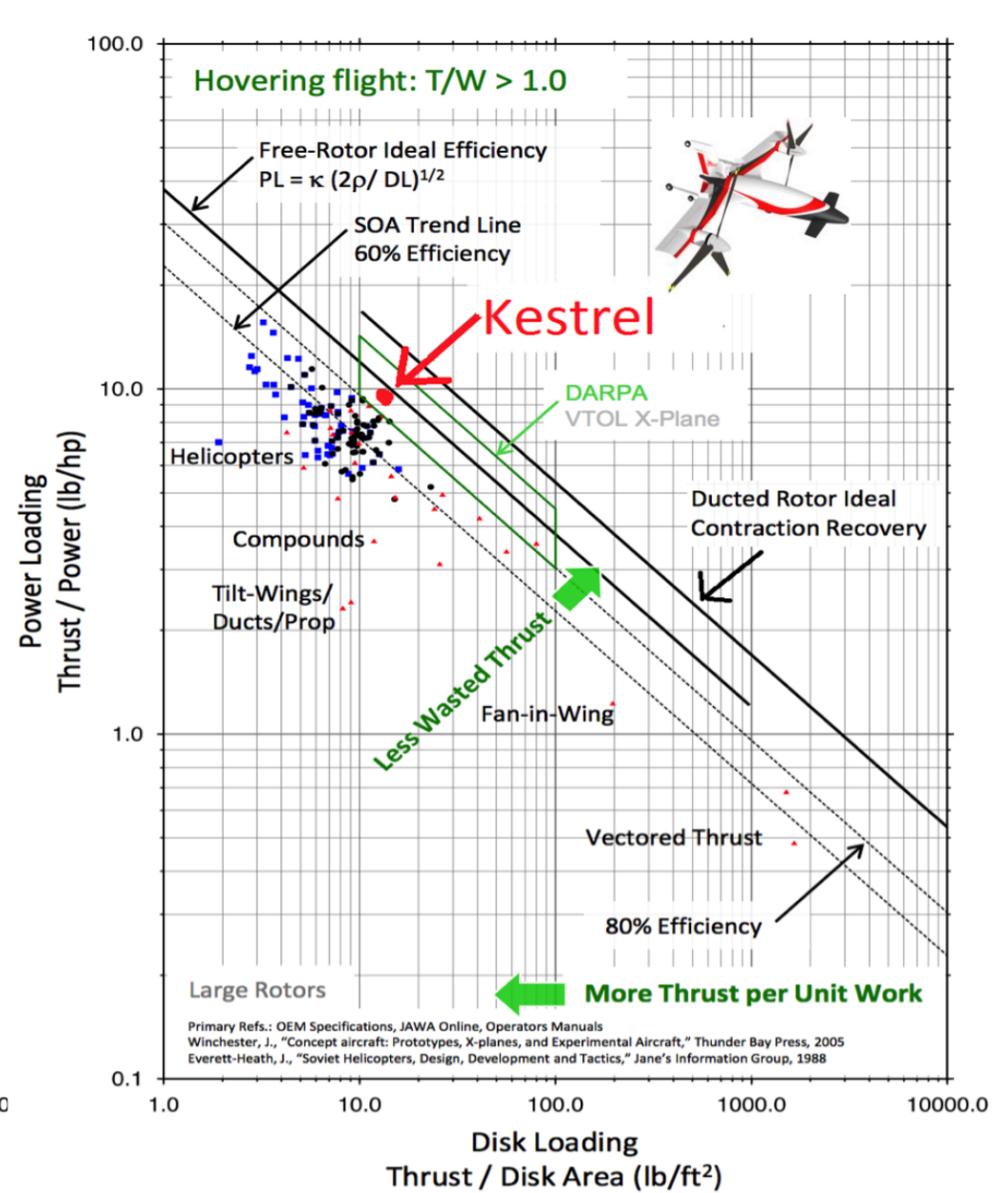
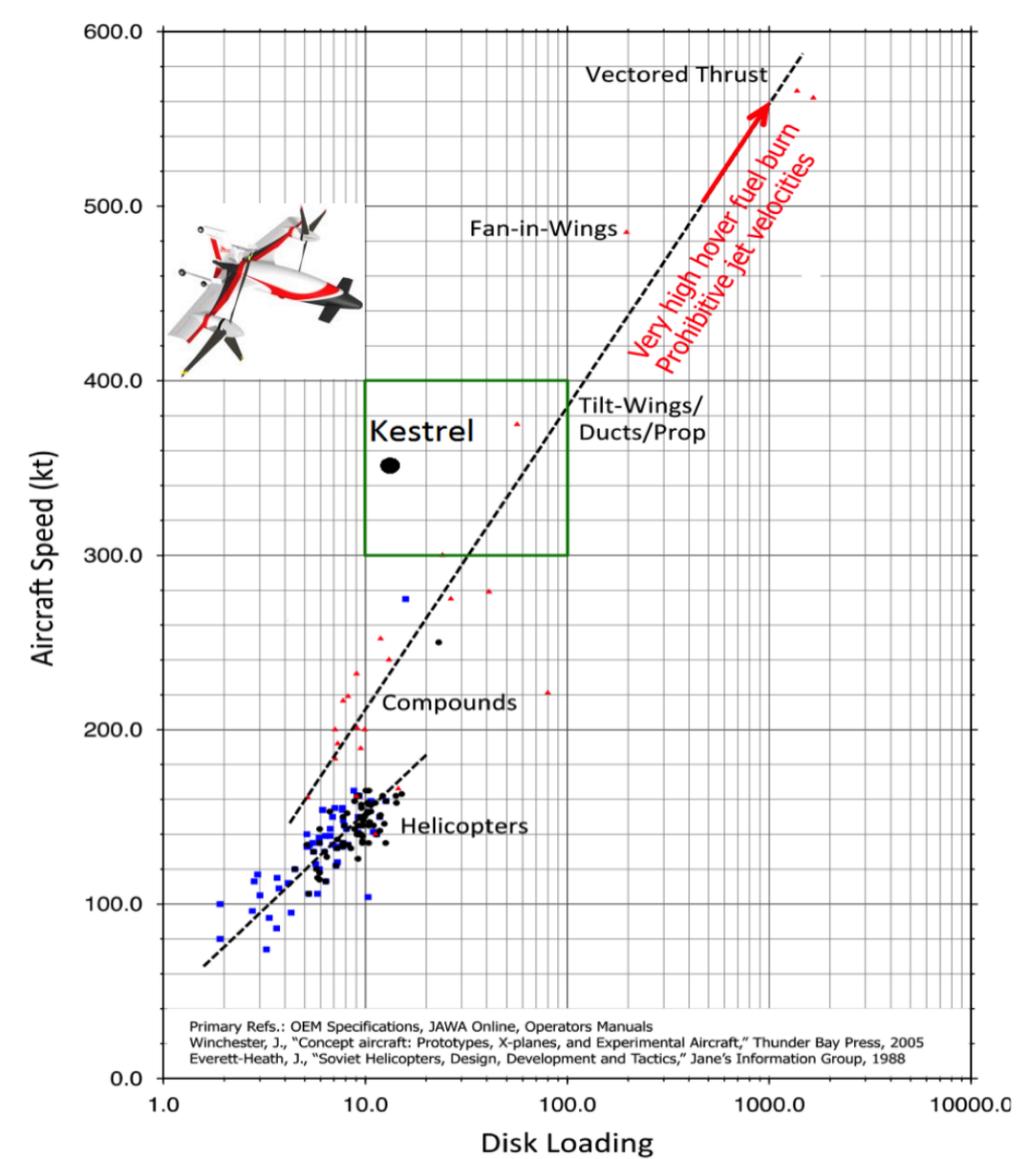
## Performance

➤ **HIGH SPEED**

The *Kestrel's* top airspeed of 350 KTAS is higher than any currently operating rotorcraft. This capability is attributed to the aerodynamically efficient fuselage shape and the absence of an edgewise rotor and hub, which can contribute approximately one-third of the total parasitic drag of a traditional helicopter.

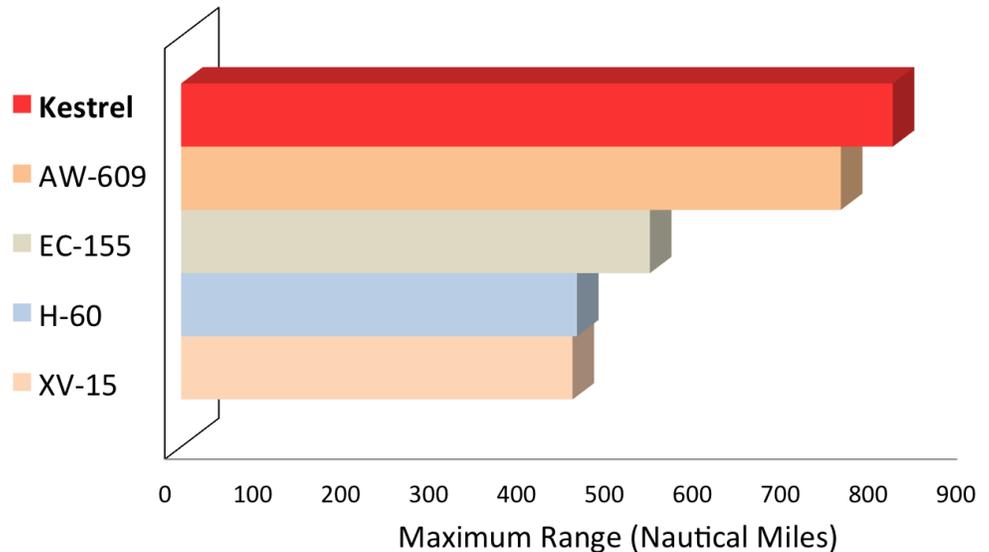


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➤ **RANGE AND ENDURANCE**

The *Kestrel*'s cruise airspeed of 200 KTAS is higher than most traditional helicopters. At this airspeed, the *Kestrel* has a maximum mission radius of 809 nautical miles and a maximum ferry range of 1,600 nautical miles; distances which are almost double that of the Bell/Boeing V-22 tiltrotor aircraft. The *Kestrel* can stay aloft for almost 11 hrs, making it well suited for information, surveillance, and reconnaissance missions.



➤ **HOVER CEILING**

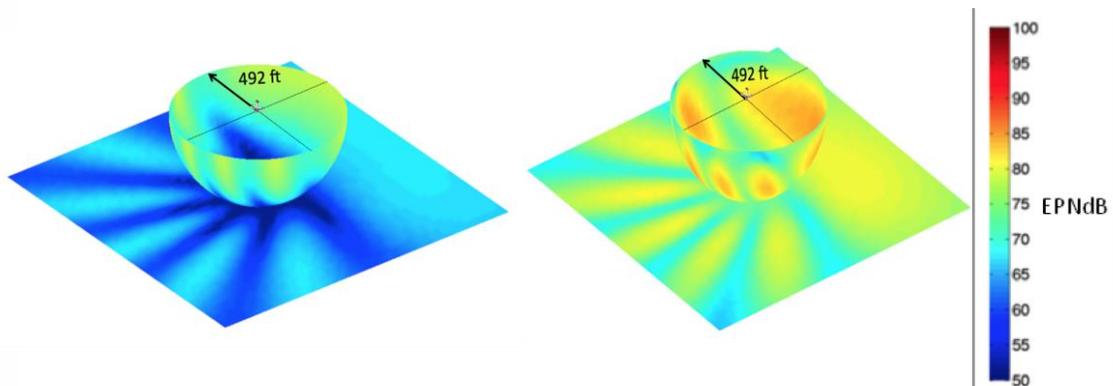
The *Kestrel* has a hover ceiling of 6K/95F (approximately 10,000 ft ISA density altitude), which is the desired ceiling for the United States Army's Joint-Multi-Role aircraft, and DARPA's VTOL X-Plane technology demonstrator.



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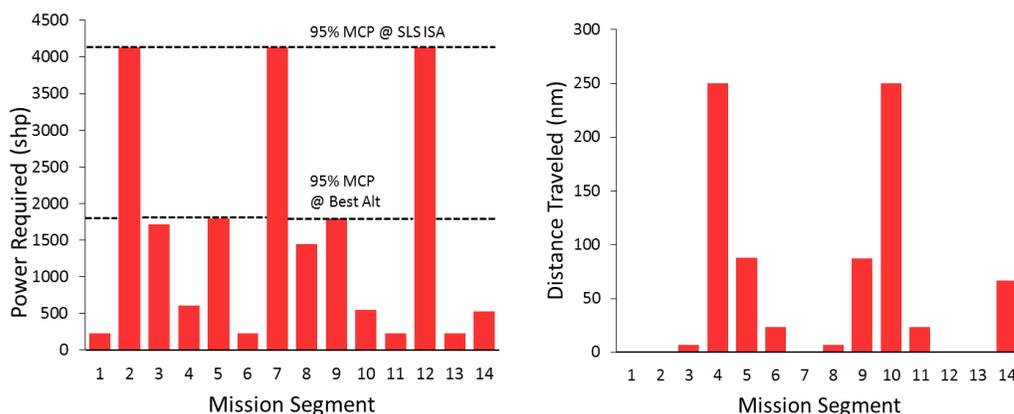
➤ **ACOUSTICS**

The *Kestrel* Complies with Part 36 of the FAA noise requirements for civilian tiltrotors as well as the ICAO regulations for takeoff, flyover, and approach. Tiltrotors and tailsitters are similar in that the proprotor plane will be parallel to the ground in hover and perpendicular to the ground in forward flight. Analysis of noise sound levels concluded that the *Kestrel* has low levels of annoyance for the human-ear. In forward flight mode the *Kestrel* has a reduced noise signature upon approach when compared to conventional VTOL aircraft.



➤ **RFP MISSION SIMULATION**

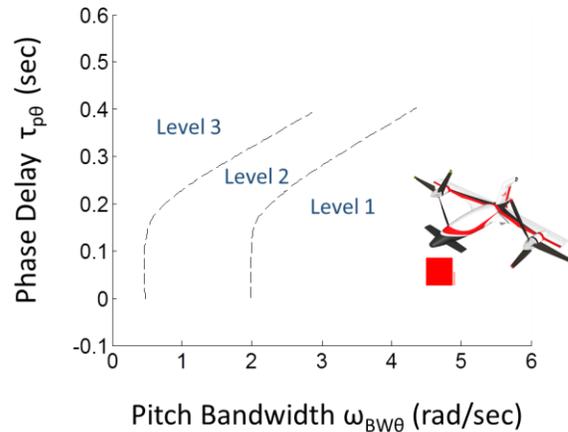
A mission simulation was performed to simulate the *Kestrel's* performance against the mission profile specified by the AHS RFP. Because the cruise distance and speed was not specified in the RFP, if the design was optimized such that the *Kestrel's* design has a 250 nautical miles cruise out segment and a 350 KTAS maximum airspeed segment. The total mission distance is 735 nautical miles and the operating altitude for the cruise and maximum airspeed segments is 9,180 ft ISA. The *Kestrel's* hover power loading efficiency at SLS conditions is 82% the of ideal power loading.



➤ **HANDLING QUALITIES**

A handling qualities analysis was conducted in FLIGHTLAB, a high fidelity rotorcraft simulation tool, validated the *Kestrel's* design by assessing its handling qualities as specified by ADS-33 standards. This capability ensures that during remotely piloted operations, the *Kestrel* would not exhibit any undesirable flying qualities. Overall, simulation results suggest that the *Kestrel* can adequately perform target tracking and acquisition missions with superior handling qualities.

Target Tracking and Acquisition

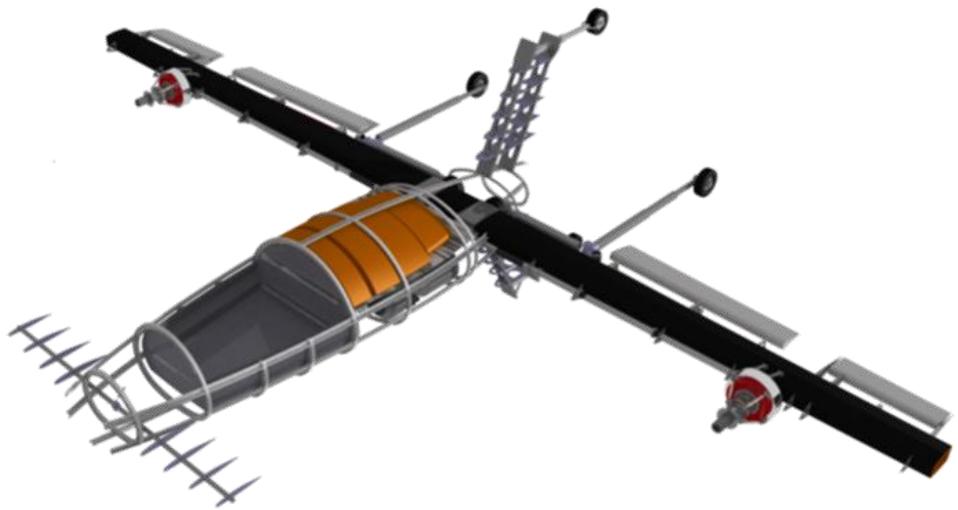


## Efficiency

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➤ **AIRCRAFT WEIGHT**

Typically, VTOL aircraft have empty weights of around a 60% of their maximum gross takeoff weight. However, these aircraft do not possess the same high performance capabilities as the *Kestrel* which has an empty weight fraction of 57% of MGTOW. The *Kestrel's* weight efficiency comes from its mechanically simple design and the use of composites in the rotor blades and wing torque box. Because it uses the same propulsion system for hovering and forward flight modes, The *Kestrel* does not suffer from weight penalties associated with complex propulsion systems such as those found on thrust compounding configurations such as the Sikorsky X2 and Airbus Helicopters X<sup>3</sup>.



➤ **DUAL-SPEED GEARBOX**

The *Kestrel* implements a novel dual-speed gearbox design to maintain a high propulsive efficiency over a range of airspeeds. The two speeds allow for an uncompromised design to maximize the forward flight efficiency and maximum range while still achieving a high top airspeed.

**Dual Speed Main  
Gearbox**

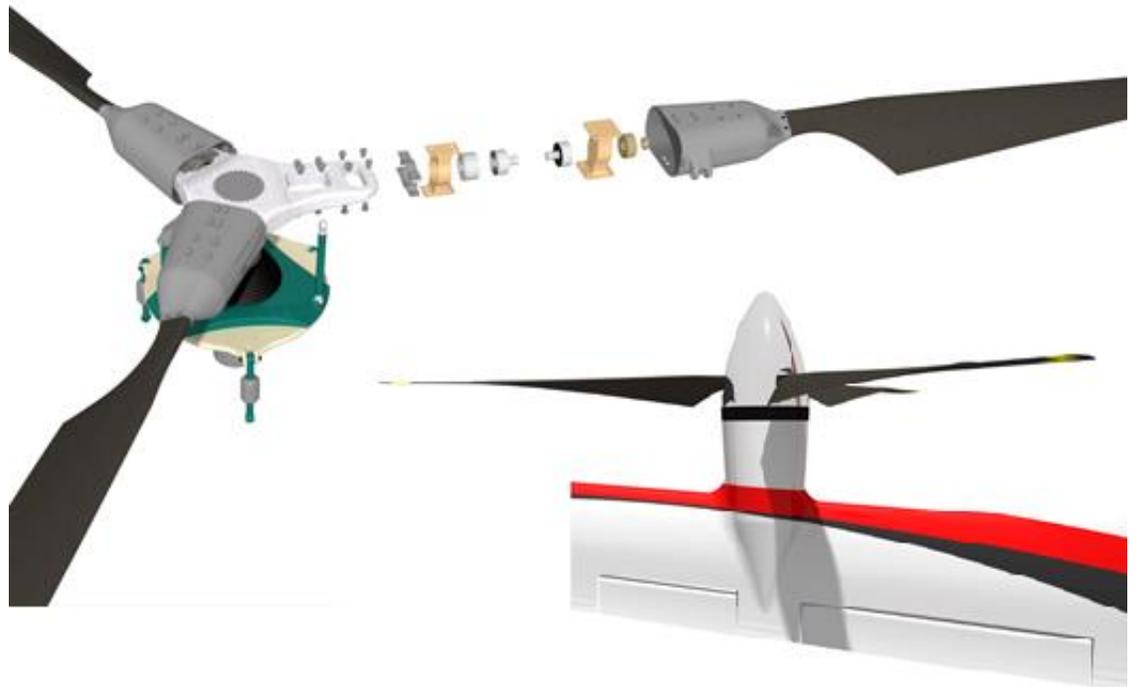


**Nacelle Planetary  
Gearbox**

The *Kestrel* achieves full reduction of the 6,000 rpm engine output shaft speed to the 269 rpm and 555 rpm outputs speeds by utilizing auxiliary planetary gearboxes located in the nacelles in conjunction to the main dual-speed gearbox.

➤ **HOVERING FLIGHT**

The *Kestrel's* large rotors give it a higher hover power loading efficiency of 82% of the ideal power loading. This efficiency is achieved by utilizing two optimized airfoil sections for the blades, which includes along with a linear chord distribution and a bimodal hyperbolic and linear twist distribution. Such a high power loading efficiency is significant because the same hovering efficient rotors also propel the aircraft to 350 KTAS airspeed with high forward flight efficiency, two flight regimes which typical command geometrically vastly different blades.



➤ **FORWARD FLIGHT**

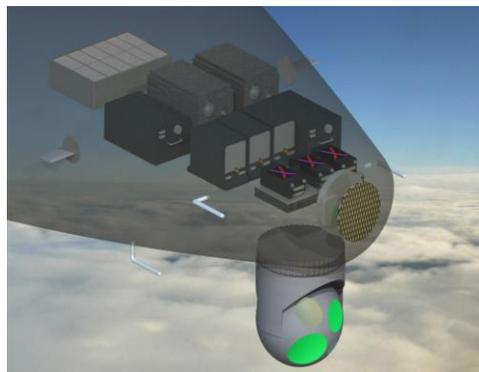
A significant advantage of fixed-wing aircraft over traditional single main rotor helicopters is the considerably higher vehicle lift-to-drag ratio of fixed-wing aircraft, which reduces forward flight power requirements and increases range. The *Kestrel* achieves an 11.9 lift-to-drag ratio, higher than any currently produced rotorcraft, because of its high aspect ratio fixed-wings and a streamlined fuselage. The wing-mounted landing gear is retractable and the tail mounted landing gear is faired to minimize profile drag.

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# Automation

## ➤ AUTONOMOUS OPERATION

The *Kestrel*'s main mode of operation is the fully autonomous unmanned flight mode. The extensive onboard avionics suite includes triple redundancy in the flight controllers, navigation equipment, and communication equipment to ensure safe and reliable operation. Even though the FAA does not specify an avionics minimum equipment list (MEL) for unmanned vehicles, the basis of the *Kestrel*'s avionics suite is the Day VFR MEL. Some equipment such as cockpit gauges were not installed on board, but their outputs do appear on the *Kestrel*'s ground control system.

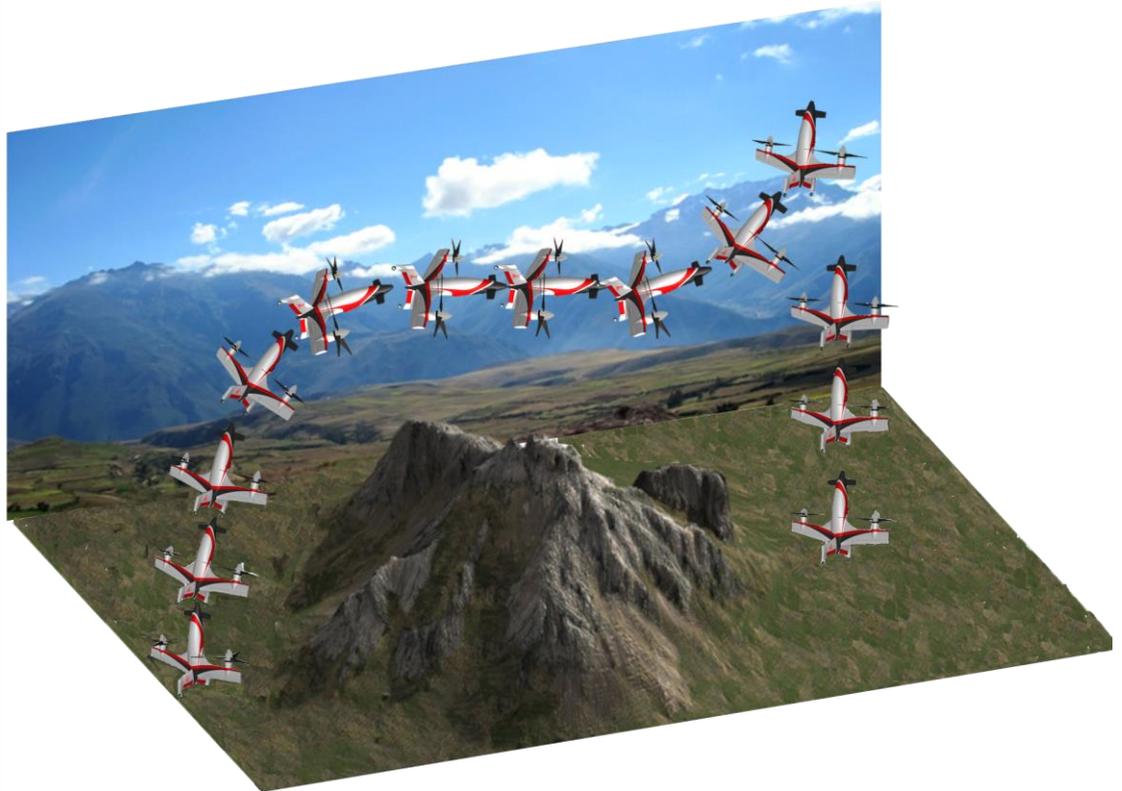


## ➤ REMOTELY PILOTED OPTION

Even though the *Kestrel* is capable of flying autonomously, the remote pilot option was included to increase situational awareness and to act as an additional redundancy in the event of sensor failure or autonomous system malfunction. A remotely piloted or semi-autonomous operation may be required in certain military applications. The pilot can command the *Kestrel* from a mobile ground control station designed to be its communication and navigation hub. A unique feature of the *Kestrel*'s pilot controls is the inclusion of separate controls for helicopter and forward flight modes. This physical indication as to which flight mode the pilot is currently in, helps to reduce the chance of pilot confusion, a common problem with using the same set of flight controls for both modes of operation.

## ➤ AUTOMATED MANUEVERS

While in remotely piloted operation, the *Kestrel* still maintains a level of autonomy to reduce the pilot's workload. Past tailsitter design of the 1950s were impractical because of the unfavorable pilot orientation during takeoff and landing. The *Kestrel* solves this issue in two ways, the first being autonomous or remotely piloted operation to remove the pilot from the aircraft altogether, and the second is by automating the takeoff, landing, and transitioning to and from helicopter and fixed-wing flight modes. The pilot simply has to flip a switch to initiate the maneuver and the *Kestrel's* flight computers take control.



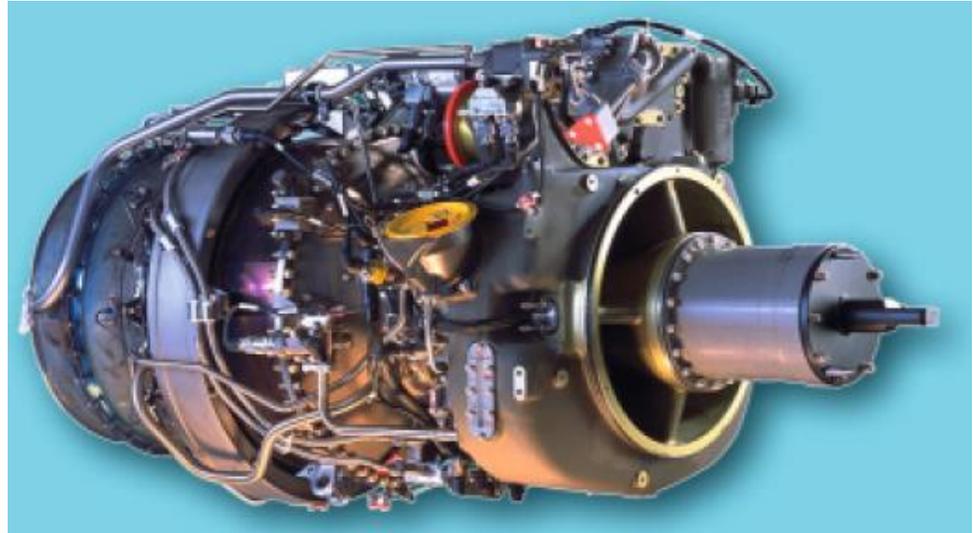
Transition maneuvers are automated through a feedback control system using inertial measurements augmented with aerodynamic state information provided by an integrated flow field sensing system, an array of embedded differential pressure sensors are distributed across the wing and canard. These measurements allow the control system to optimize the control mixing ratios and change control modes depending on actual flight conditions.

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# Affordability

## ➤ POWER UNIT

As specified by the RFP, the *Kestrel* is powered by currently available production engine. Two Turbomeca RTM 322 01/9 turboshaft engines power the *Kestrel* for a total maximum continuous power of 4,454 shp at sea level. The RTM 322 has been in service since 1998 and currently powers the AgustaWestland Apache, the AW 101 Merlin, and the NHIndustries NH90 helicopters. Using this engine allows the *Kestrel* to take advantage of the 16 years of proven technology and reliability, which reduces maintenance costs.



## ➤ TOTAL COST

The *Kestrel*'s estimated acquisition cost to build a technology demonstrator is \$19.1 million. The DARPA X-Plane Program has been allocated \$130 million for the entire program, with \$47 million for Phase IA/B, leaving \$83 million for the remaining two teams entering Phase II/III. Split evenly between the two teams, the *Kestrel* will require only \$22.4 million for the Phase II (18-month Development and Integration), and Phase III (12-month Ground and Flight Testing).

	Acquisition Cost	Direct Operating Cost	Indirect Operating Cost
EC-155	10.6 (\$M)	2,220 \$/FH	544,755 \$/year
Kestrel	19.1 (\$M)	2,278 \$/FH	476,604 \$/year

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# Concept of Operations

The *Kestrel* is a force multiplier that is well suited for a variety of tasking by enhancing the capabilities of other systems it interfaces with. The extraordinary performance of the *Kestrel* enables it to fulfill a variety of roles and surpass the capabilities of legacy systems.



- **Intelligence, Surveillance, Reconnaissance (ISR) Capability** – Whenever the tasking is too repetitive or dangerous, the *Kestrel* can provide support to gather necessary information. For missions that required speed or range the *Kestrel* is an ideal ISR platform.
- **Cargo Delivery** – The *Kestrel's* unprecedented range and airspeed capabilities with its useful load capacity, the *Kestrel* is well suited from efficient logistical support to quick response disaster relief.
- **Shipboard Compatibility** – The *Kestrel* is designed to be a capable platform for shipboard missions. The *Kestrel* utilizes composites and anti-corrosion treatment. The *Kestrel* also incorporates electromagnetic shielding to safely operate on or around a ship's surface.
- **Communication Relay** – Many legacy systems currently in service are limited by line-of-sight (LOS) communications. The *Kestrel* can increase the effective range of other systems by acting as a flying cell tower to transform LOS limited vehicles into over-the-horizon platforms.
- **Reconfigurable Internal Payload Bay** – To meet the future capability needs, the *Kestrel* has a reconfigurable internal payload bay which can support a variety of specialized subsystems such as aerial refueling.



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# RFP Compliance Checklist

RFP Requirements	<i>Kestrel</i> Performance	Requirement Met?
Sustained high airspeed flight: 300 – 400 KTAS	Maximum continuous airspeed: 350 KTAS	
Aircraft hovering efficiency within 25% of ideal power loading	Hover efficiency = 18% of ideal power loading	 Exceeded by 9.3%
Change maximum aircraft cruise lift-to-drag ratio $\geq 10$	Best lift-to-drag ratio = 11.9	 Exceeded by 19%
Useful load fraction $\geq 40\%$ gross weight, payload fraction $\geq 12.5\%$ gross weight	Useful load fraction = 40% gross weight, payload fraction = 12.5% gross weight	
Maximum gross weight: 10,000 – 12,000 lb	Maximum gross weight = 10,942 lbs	

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## Conclusions

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The *Kestrel* represents a synergy of current aircraft systems to radically expand the flight envelope of future VTOL aircraft. The *Kestrel* improves performance and efficiency over the current state of the art by utilizing dual-speed transmission, which enables unprecedented forward flight efficiency. Utilizing advanced controls system and guidance laws, the *Kestrel* is capable of autonomous and remotely piloted flight throughout all flight modes. The high-speed capability surpasses the performance of any VTOL aircraft currently in production. The *Kestrel* is a cost effective solution with multi-mission capability to expand the role of the next generation of VTOL aircraft.



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