High-Speed Solar Aircraft and SP-Drone

Contents

STATEMENT ON PROPRIETARY STATUS

Definitions:

AoA -	Air angle of attack.
AR -	Aspect ratio.
Camber (“c”) –	Herein reported camber is maximum camber, which is the maximum distance the camber line varies from the chord line divided by the chord length multiplied times 100 (or reported as a percent).
C_{DI} -	C is for coefficient, D is for drag, I is for induced.
C_l -	Lift coefficient.
CFD -	Computational Fluid Dynamics
e -	Efficiency factor.
g -	Gravity acceleration, 9.8 m/s^2.
HAPS/HALE -	High-altitude platform-station, high-altitude pseudo-satellite, high altitude long endurance.
L/D -	Lift-drag ratio.
m -	Meter.
Pa -	Pascal unit of pressure.
Power Ratio –	Ratio of power produced by photovoltaic cells on a surface divided by the power needed to overcome the drag of that surface.
P_{PV} -	Power produced by photovoltaic cell array.
RC -	Remote control.
Re -	Reynolds number.
SP-Drone –	Solar Platform Drone, it is an airframe technology of this project.
t -	Thickness.
Towed Platform –	A platform towed by a lead aircraft to form an airframe. Typically the Towed Platform is thin and configured to operated at a thin-plate airfoil.
U -	Velocity.
v -	Viscosity.
VTOL -	Vertical Takeoff and Landing aircraft.

Part 2: Identification and Significance of the Proposed Innovation

Current guidelines in aircraft design point toward: a) high-aspect-ratio wings for efficiency and b) swept-wing or delta wing airframes for higher speeds. These guidelines fail in the limits of very low wing loadings, thin-plate cambered airfoils, and the complexities of a complete design.

This Phase I NASA SBIR proposal has the following over-arching principles:

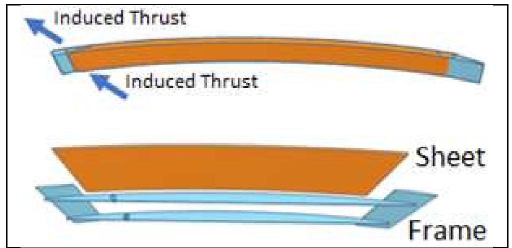

Figure 1. Induced thrust, sheet, and frame of thin-plate cambered airfoil.

- Simple single-sheet cambered-airfoil-on-a-frame design (Figure 1).
- Towed Platform stability and robustness.
- Low aspect ratio design using informed optimization decisions.

The **simple design** allows for rapid fabrication for R&D and design evolution followed by low manufacturing cost; in this case, the simple fabrication complements thin-plate cambered airfoil technology which is more efficient than any other airfoil design. The **Towed Platform technology** transforms an otherwise pitch-unstable design to an inherently stable design with a built-in control surface (lead aircraft) that eliminates the need for an additional horizontal stabilizer. The base case **low aspect ratio** reduces the L/D; however, the manner in which the propulsor is integrated into the design (as well as other vortex mitigation features) can trump performance deterioration from trailing edge vortex formation of low aspect ratio airfoils.

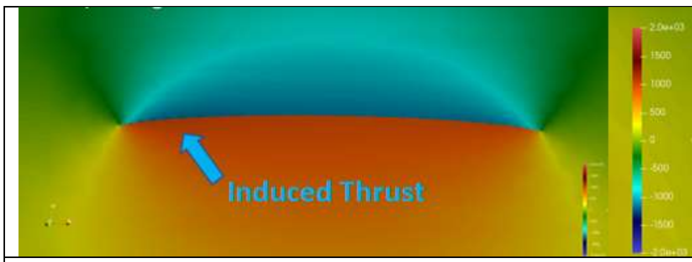

Figure 2. Pressure (Pa) about a thin-plate cambered airfoil.

The reason the thin-plate cambered airfoil is more efficient than any other airfoil, when optimized, is because it maximizes induced thrust (see Figures 1 and 2) on both upper and lower airfoil surfaces. The reason the Towed Platform is inherently stable is because perturbations that lower lift on the Towed Platform increase the average AoAs resulting in a compensating increased lift. An upward displacement at the Towed Platform's leading edge points the aircraft leading edge downward resulting in a compensating downward force on the Towed Platform. The reason the Towed Platform increases robustness is because longitudinal flexibility is a robust design feature. The reason informed decisions trump guidelines on the impact of low aspect ratios is that a lead propulsor generates dynamic pressures that are greater than pressure forces of trailing edge vortices.

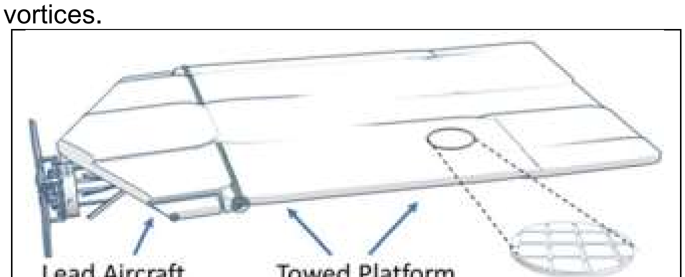

Figure 3. A version of SP-Drone.

Thin-plate cambered airfoils can achieve L/D in excess of 100 (Osei et. al., 2020; Winslow et. al., 2017). These high L/D are only possible with induced thrust, and only the thin-plate cambered airfoil has significant induced thrust on both the upper and lower surfaces (see Figure 1). Large sections of the cambered airfoil may be a thin sheet (e.g., less than 0.5 mm thick) with just sufficient frame to allow the lift forces to form the ideal camber on the sheet.

Figure 2 illustrates how the curvature of the thin-plate cambered airfoil affects the pressure profiles at steady state; this curvature can be tuned to provide a uniform and moderate lift on both upper and lower surfaces. The spanwise curvature can also be tuned to provide high lift in middle sections and to mitigate driving forces that form vortices on the sides; this enables the innovation of Figure 3 referred to as a "Towed Platform" pulled by a lead aircraft to form a Solar Platform aircraft ("SP-Drone").

The Innovation – SP-Drone is a new/novel high-speed airframe designed for use with photovoltaic cells and has the following features:

- A low-aspect-ratio thin-plate cambered flying wing. (**Significance** – This structure, alone, produces the greatest L/D of any structure).

- An airframe comprised mostly of single-layer construction where composite sheets generate lift on both their upper and lower surfaces. (**Significance** – This structure, alone, creates the maximum lift per mass of any wing or lifting-body section. The aircraft will attain high-speed solar-powered flight including 24/7 flight sustainability.)
- Longitudinal flexibility is built into airframes of 0.2 to 1.0 aspect ratio. (**Significance** – This provides a robustness in very light-weight designs for high-speed flight. It also provides more-streamlined methods to control flight than rudders, flaps, and ailerons.)

SP-Drone's airframe is not limited to drone aircraft; it is scalable to numerous applications.

Significance of Towed Platform – A key feature of SP-Drone is the Towed Platform. Preliminary estimates identify that at 280 mph (125 m/s) the Towed Platform produces 5X the energy needed to overcome its drag. This is significant because:

- The Towed Platform can be attached to and/or integrated with a wide range of lead aircraft to meet contemporary and new aircraft applications.
- This 5X power ratio is an estimate for a market-entry aircraft. This will improve with optimized airframes, improved integration with propulsors, larger scales of aircraft, and progress in photovoltaic cell technology.
- This 5X is enough to enable 24/7 flight at speeds up to 280 mph (125 m/s). These speeds increase to 560 mph (airliner speeds) for daytime service. The 24/7 flight can be expanded to 560 mph service by a number of methods such as: a) improvements in overall efficiency and photovoltaic cells, b) supplementing flight with an onboard diesel engine generator, and c) in-flight energy transfer by a variety of mechanisms (e.g., energy beams, umbilical cord transfer of electricity).
- This 5X is enough to enable 24/7 platforms including chemical/fuel production platforms and refueler aircraft. Here, refueling includes such things as energy beams and umbilical cord transfer of electrical power.

The 5X "Power Ratio" is the ratio of power produced by photovoltaic cells on a surface divided by the power needed to overcome the drag of that surface. Equation 1 provides this ratio in equation form.

$$Power\ Ratio = \frac{P_{PV}}{g\ (D/eL)\ U} \tag{1}$$

Where: $\boldsymbol{g}$ = 9.8 m/s^2,

$\boldsymbol{P_{PV}}$ is power density of photovoltaic array including wing weight (W/kg).

$\boldsymbol{U}$ is velocity (m/s) with benchmarks of 343 for sound and 250 for commercial airliner.

D/L is reciprocal of lift-drag ratio for Aspect Ratio = ∞ (2D airfoil performance),

$\boldsymbol{e}$ is an efficiency factor associated with low Aspect Ratio form (target of 0.5).

The 5X ***Power Ratio*** was calculated using: $\boldsymbol{e}$=0.5, $\boldsymbol{P_{PV}}$=300 W/kg, $\boldsymbol{g}$=9.8 m/s^2, ***L/D***=40, and $\boldsymbol{U}$=125 m/s. The sources of these values are discussed in the next section on Part 5: Related R/R&D.

Significance of "Other" – In addition to the significance cited in the previous four bullets, the following are significant:

- A focus on flight efficiency (i.e., high L/D and light weight) is typically the best way to reduce adverse environmental impacts. In this case, the high flight efficiency of this airframe, alone, reduces environmental impact by more than 50% (estimate) because the thin-plate cambered airfoil is capable of efficiencies >5X the flight efficiency of contemporary airliners. High efficiencies translate to lower costs for photovoltaic power to sustain flight; it also translates to scalability to smaller scales for the drone market. Fundamentally, SP-Drone's airframe is the most efficient possible. Several refereed papers have identified L/D in excess of 100:1 for thin cambered airfoils (i.e., thin and concave downward for >90% of the chord) ; whereas contemporary airfoils peak at about 70:1. The improved performance of the thin-plate cambered airfoil is due to the induced thrust on the front third of the lower surface. All high L/D airfoils achieve the high L/D due to induced thrust, but only thin-plate cambered airfoils have significant induced thrust on lower surfaces. This is illustrated by the pressure profile of Figure 2. Part 5 discusses preliminary CFD studies on the impact of aspect ratio and how to mitigate reductions in performance due to low aspect ratio airframes.
- Flying above the clouds (up to 2.3X), at higher levels of radiation (1.2X), against Earth's rotation at night (1.5X), and with reasonable ability to optimally orient the solar panels (1.5X); the photovoltaic cells may reach 6.2X the productivity of photovoltaic cells on Earth's surface. This

makes the energy very low cost (as low as 1 cent per kWh) from both dollar and environmental-impact costs. Mass production of Towed Platform units and time (lower cost photovoltaic cells at higher efficiency) will take these costs down to 0.5 cents per kWh for aircraft that operate essentially continuously during daylight.

- The afore-mentioned 50% reduction in energy needs and low energy costs (e.g., 1 cent/kWh) translate to a staggering reduction (>90%, jet fuel alone costs about 18 cents/kWh) in annualized costs of transportation, enough to redefine the techno-commercial infrastructure of humanity.
- The upside potential of this technology is huge, at an unprecedented scale, including the following:
  - Worldwide patent protection can secure the vast majority of manufacturing (and innovation associated with those doing the manufacturing) to entities looking after the interests of the United State. This position is possible for decades to come.
  - Scalability makes the SP-Drone competitive in transport of essentially all the transport sectors (replacing much of truck and ship transport). To a first approximation, the L/D is a function of Reynolds number ("***Re***") for a given airfoil and average AoA. Here Re = ***U c / v***; where ***U*** is velocity, ***c*** is chord length, and ***v*** is viscosity. Typical trends in L/D are as illustrated by Figure 4, where ***L/D*** increases with increasing ***Re*** . These combine to identify that increasing the scale (i.e. chord length "***c***") increases ***L/D***. This has been confirmed by CFD simulations on the SP-Drone project. The ***L/D*** are incredible on the small scale being over 100 at ***c*** = 1 m; and it increases with larger scales.

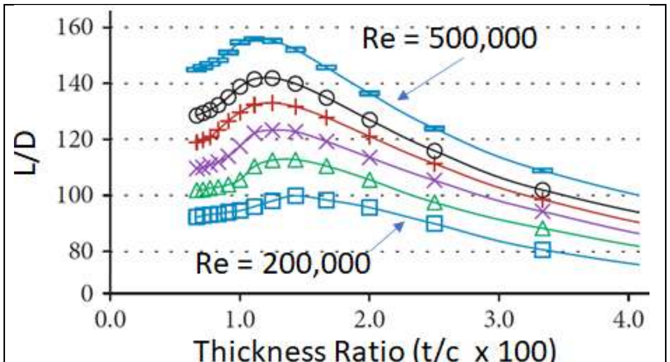

Figure 4. Increase in ***L/D*** for thin-plate cambered airfoil. Continuous increase from 100k to 500k ***Re***. Osei et al.

  - All Transport Sectors will lose to competition with SP-Drone. The energy costs of as low as 1 cent per kWh are superior to all competition. Patent US10,589,383 (plus other continuations in part) protects approaches to transform a VTOL to an SP-Drone configuration; and so, SP-Drone is competitive at short haul as well as long haul. Constructions costs are ultra-low (single-sheet composite airframes), and the vehicle turnaround between loads is fast. Even large ships crossing oceans will be unable to compete for most of the market.
  - Telecom and Wifi Sectors served by HAPS/HALE versions of SP-Drone will replace most of satellite markets for two reasons: a) the altitude is low enough for contemporary telecom signals and modified WiFi signals and b) any city of reasonable size can afford their own HAPS/HALE aircraft (i.e., The monopoly will be by the holder of the patents rather than the deep pockets to launch satellites). One HAPS would provide the service equivalent of 250 cell towers.
  - Military Dominance can change because inexpensive drones will be able to reach any location on the globe from any launch site. These drones will be stealthy and will fly at altitudes that are beyond most defenses, and at the least, altitudes where countermeasures can take out adversaries due to superior high-altitude positions.
  - Space Access on Routine Basis will be available from airborne aircraft carriers cruising at altitudes of 120,000 to 150,000 ft. The carriers will primarily tow drone aircraft, but a variety of carrier capabilities are possible. These high altitudes are beyond the booster rocket stage of the now-retired space shuttle, making it much easier for an aircraft to achieve roundtrips without booster rockets. These carriers will provide electric power, hydrogen, oxygen, and ammonia to the aircraft they carry; all of these chemicals will be produced onboard from gases collected in the atmosphere.
  - Stratospheric Frontiers are above the turbulence of lower altitudes and allow for 24/7 platforms to provide a variety of purposes, including but not limited to: a) production of

hydrogen and ammonia for delivery to Earth's surface using low-cost solar energy, b) flying to provide connections between flights, and c) flying cruise ships/hotels.

- Complementary Technologies include photovoltaic cells, electric motors, electric propulsion, hybrid electric-fuel engines, and drone-based agriculture. SP-Drone will create markets to advance other technologies of great importance to mankind.
- Refueler aircraft versions of SP-Drone were mentioned previously. However, the importance cannot be under estimated since refueler aircraft enable applications to essentially all aircraft applications; they are an additional degree of freedom to provide faster, better, and lower-cost service.

Significance: Engineering Lift-Generating Surfaces – The optimization of a thin-plate cambered airfoil is simplified under the constraint of a constant airfoil thickness (except for leading and trailing edges). This simplification is enough to allow the airfoil shape to be treated as part of the overall aircraft optimization. In view of the fact that evidence suggests that the thin-plate cambered plate airfoil is the "most efficient" airfoil possible, this approach allows for aircraft optimization at a level not previously attained. Granted, these designs limit the structural load transfer ability across an airfoil, but this is less relevant for Towed Platform airframes. This is discussed further in the preliminary results section of the Part 4 Work Plan.

Relative to Current State of Art – Three benchmarks stand out as the current state of the art: 1) the delta wing versus the substantially rectangular platform, b) HAPS/HALE prototypes, and c) XSun.

1) Delta Wing - The delta wing often approaches a thin-plate cambered wing configuration (e.g., the concord). The preferred design of this project is a delta wing leading a Towed Platform as illustrated by Figure 3. For the Figure 3 design, the forces that cause wingtip vortices, transform, to form a trailing edge vortex. Will the optimized version of the Figure 3 airframe reduce to the contemporary delta wing design? The answer lies in advanced CFD and digital twin studies which are part of this effort. However, there are factors that overwhelmingly suggest that the optimum will be a variation of the Towed platform design. These factors are:

a) The ultra-light design of a composite sheet configured as a thin-plate cambered airfoil combined with the designs synergy with being "pulled". The pulled sheet is lighter in weight and lower in cost than the structural delta wing. The ultra-light weight and respective light wing loadings have not been optimized (beyond low-cost hang gliders).

b) Exo-frame (see Figure 1) aspects of the design create a synergy with vanes and fences, and so, the mass and cost of these are already part of the Towed Platform.

c) The position and design of the lead propulsor; wherein, the dynamic pressure of its backwash will easily overwhelm the pressure forces causing tail vortex formation.

d) A lead delta wing with a serrated Towed Platform trailing edge (e.g., the B2 bomber).

These degrees of freedom are a valid basis for excitement on this project and its potential.

2) HAPS/HALE - HAPS/HALE prototypes (see Table 2) are basically different versions of the same design. That design is use of high-aspect-ratio light-weight-construction wings. Benchmark L/D for such construction methods are: Nasa's Pathfinder Plus at ***L/D*** = 21, the ASH 31 glider (AR=33.5) at ***L/D***=56, and the Eta motor glider (AR=51.33) at ***L/D*** = 70. Based on a comparison of weight-to-power ratios by Mattos et al (2013), the Zephyr has a ***L/D*** of about 24; this L/D is consistent with published photographs revealing a wing aspect ratio of about 24:1; the estimated range of L/D for the HAPS/HALE aircraft is 22 to 30. Targeted L/D for HS-Drone is >40 for initial smaller drone systems and >60 for larger scales. Figure 5 illustrates the fragile and bulky AeroVironment Helios Prototype.

Figure 5. Evolution of HAPS/HALE.

3) XSun and New Generation Aircraft – Figure 5 compares XSun's SolarOne to SULE and HELIOS. XSun uses two sequential wings and a fuselage having an airfoil-type shape. Using multiple sequential wings is an approach claimed to achieve higher efficiencies with the developers of the Tri-Wing Jumbo Jet (Figure 6) claiming significant increases in

efficiency. Methods being pursued to improve efficiency are: a) use of thinner wings, b) use of sequential wings, and c) improved use of lifting body technology. Boeing has scheduled production of a new truss-braced wing aircraft which claims a 30% increase in efficiency. Figure 7 illustrates the following features of this aircraft) a) thinner wings, b) attachment to the top of the fuselage to minimize interference between fuselage and wing, and c) an airfoil shape on the fuselage that complements the wings airfoil shape.

Table 2. Summary of HAPS/HALE prototypes (Peck, 2020).

	APUS DUO	Odysseus	PHASA-35°	SULE	Sunglider	Zephyr
Manufacturer	UAVOS	Aurora/Boeing	Prismatic/BAE	Swift Engineering	AeroVironment	Airbus
Stated advantage	Autopilot; 1,000 hours of earlier test flights	Large payload; 35-degree latitude	"World class" 31 percent battery array efficiency	NASA collaboration, light weight, high tech, high ceiling	Payload, interoperability, HAPS history	"Only HAPS to have demonstrated day/night longevity in the stratosphere"
Wingspan (ft)	46 current; 197 under discussion	243	115	72	262	82
Operatingaltitude (ft)	66,000	60,000	65,000	70,000	62,500	69,800
Airspeed (mph)	60	N/A	Close to 60	45-69	68	35 (Zephyr 7)
Propellers/engines	1-3	6	2	2	10	2
Payload (lb)	18; 33 planned	55	33-55	15	150	33
Takeoff/landing	Fully automatic; ground equipment not required	Towed and released	Releasable launch gear system; lands directly on structure	Currently four-bar linkage release; lands on skin plates	Towed to runway	Hand-launched by 3-4 people

SP-Drone stands out among the competition with the following features:

- Use of large single-sheet wing sections that are low cost and ultra-low weight.
- Use of induced thrust on the lower surface.
- New levels of engineering for lead propulsor placement and operation.

Figure 6. Competitions' next generation airliner designs.

Figure 7. Boeing's truss-braced wing with airfoil extending above fuselage. High wing offers least interference.

Part 3: Technical Objectives

This SP-Drone project has a 3-year goal to roll out a breakthrough high-speed solar-powered aircraft capable of 24/7 flight with global range and scalability. This NASA Phase I investigation has the following objectives:

- Prototype and demonstrate the novel airframe at 500 gram and 2 kg scales as remote-controlled ("RC") battery-powered aircraft. This includes refining the fabrication method for rapid prototyping.
- Develop a CFD digital twin of SP-Drone and validate the digital twin with actual performance of the airframe prototype.
- Use the CFD digital twin to optimize the design and scale performance toward: a) improving the performance of SP-Drone, b) scaling the design to project performance of SP-Drone for different applications, and c) preparing a bill of materials and team for a Phase II investigation.
- Perform engineering calculations as needed to complete the bill of materials for an initial Phase II prototype.

While a Phase I investigation emphasizes the airframe; the Phase II program will build a solar-powered aircraft toward sustained 24/7 operation. It is anticipated that 24/7 operation with SP-Drone will be possible on much smaller scales (e.g. 5' wingspan versus 72' wingspan), lower costs, and less-complex fabrication methods than all alternative 24/7 aircraft (excluding lighter-than-air craft).

Part 4: Work Plan

Four work plan tasks are aligned with the objectives per the following sections:

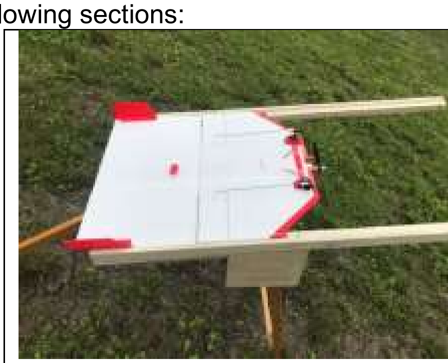

Figure 8. Prototype on takeoff ramp.

1. Fabricate, Test, Advance Prototype Figure 8 illustrates a summer 2022 prototype and takeoff ramp. Much has been learned since summer 2022 when prototypes were very much trial-and-error. The new generation of prototypes will be based on designs vetted with preliminary CFD studies. The takeoff ramp approach worked well in 2022, and will continue to be the standard.

The new generation of prototypes evolve toward thin carbon fiber sheets having a stiffness between that of laminated plastic and cloth. A servo ("Servo 1") will control the angle between the lead aircraft and the Towed Platform; Servo 1 will include a spring-based tension (e.g. a shock absorber) to allow passive response to perturbations that would impact pitch stability. Leading edge ailerons ("Servo 2") will be used so as to allow a contiguous and smooth camber from leading to trailing edge.

Prototypes are operated from a Spectrum DX6e transmitter (6.4 GHz, 6 channel, built-in telemetry) and SPMAR630 6CH receiver/stabilizer. That control system will be further enabled with a telemetry GPS sensor and laptop/software to record location, speed, and other information. The latest sensors will be researched to identify the best method to measure both power consumption and velocity.

Testing channel assignments include: a) channel 1 to electronic speed control, b) channel 2 to servo 1, and c) channel 3 to Servo 2. Three channels and six transmitter switches are available to control additional [control] surfaces and for telemetry interaction. Test flights are conducted at RC Test Field in Charlottesville, VA. **Desired outcomes** include a progression of prototypes exhibiting extended flight with data on speed and flight efficiency. **Resources** include 300 hours of the PI time and all supplies and materials except for the CFD license (and any computer upgrades).

A "More-Detailed Discussion of Prototyping" is provided at the end of this section.

2. Develop and Validate CFD Digital Twin – SimFlow CFD calculations are being used to estimate L/D, drag coefficients, pressure coefficients, moment coefficients, and respective extensive properties like lift and drag. Paraview is used to visualize the pressure and velocity profiles/streamlines to understand trends. These methods will be used on geometries of increasing complexity to create a digital twins of the Task 1 prototypes, to validate the digital twin, and to better understand the performance of the prototypes.

The digital twin has various stages of complexity with initial verification being only of aerodynamic flow around geometries and latter stages including sources terms (i.e., propulsors). Validation of energy consumption of the prototype, absent propulsor simulation, will be sufficient to provide increased confidence and proceed with the specification of a bill of materials and scale specification for the Phase II investigation. The Phase II investigation will proceed to identify the first commercial product and minimum scale for sustained 24/7 flight to better identify the competitive advantages in the many markets.

The Phase I investigation will initiate source-term simulations on the digital twin which can be used to identify both the type of blades to use and the impact of the propulsor on aerodynamic characteristics. These initial studies will identify what can reasonably be achieved in a Phase II investigation. These initial studies will also identify the prospects and benefits of commercial and DOD needs beyond the anticipated Phase II investigation.

The source term simulations are important to evaluate the impact of the propulsor on trailing edge vortex formation; which is a primary source of lost L/D at low aspect ratios. **Desired outcomes** include CFD results similar to measured prototype performance. **Resources** include 200 hours of the Research Engineer time, the CFD software license, and computer upgrades.

3. Use Digital Twin to Understand Impact of Scaleup and Edge Effects Flat Plate Airfoil – While the previous task was on developing the CFD Digital Twin focus, this task has a focus on using the digital twin to evaluate scaling and more-advanced solutions to mitigating L/D losses at low aspect ratios. New design features will be used to improve prototype designs. Those prototypes will be built and their performance evaluated. The results will be used to improve the CFD simulations.

A key aspect of these studies is to evaluate the performance advantages of Towed Platform designs against contemporary counterparts like the delta wing. And so, CFD simulations will also be performed on delta wing benchmarks.

Preliminary studies will be performed on the addition of a fuselage with weight distributed to both the lead aircraft and towed platform. These will provide a basis for future work on designs for passenger service and hauling of freight.

Planned outcomes/accomplishment include:

- Multiple generations of prototype aircraft that demonstrate flight control and high efficiency of a Towed Platform Aircraft.
- Understanding of how scaleup and fence geometries impact the L/D of a Towed Platform.

Desired outcomes include a comparison of design evolutions to one another and to base case delta wing designs. **Resources** include the balance of time (from other tasks) for both the PI and Research Engineer.

4. Specification, Paper Study, and Bill of Material Preparation for Phase II – Communications with the NASA program manager will be used to identify a suitable Phase II prototype. What is possible:

- A Phase II prototype at a scale up to 125 lbs with testing at the Charlottesville field.
- The design of the Towed Platform at a scale of 10' X 5'.
- Approval for flight at an alternative field that will allow aircraft larger than 125 lbs combined with identification of resources to build this larger aircraft.

Based on the size and completeness of a Phase II prototype as determined with the NASA program manager, the results of Tasks 1 and 2 will be used to specify the bill of materials for the Phase II prototype. This bill of materials will include the specification of solar panels and control systems to provide the required power output. A paper study will be used to complete any specifications such as size and weight of batteries. The paper study will include an estimate of flight efficiency which will be used to specify the solar panels.

Planned outcomes/accomplishment include:

- A bill of materials for a Phase II prototype along with a submitted Phase II proposal.

Resources include 100 hours of the PI's time.

More-Detailed Discussion of Prototyping – In 2022, bursts of prototyping effort included the fabrication and testing of up to three prototypes in 24-hour cycles. This is possible when strategically-designed 3D-Printed Coupling Devices allow the rapid assembly of beams, sheets, and electronics. The 2022 efforts were trial-and-error in nature. The challenge was to effectively use Towed Platforms to generate lift. The closest approach to the Towed Platform is the delta wing, but the aerodynamics of the delta wing are quite different; and it is relatively easy to design an RC aircraft that uses the delta wing configuration. Design details are much more important for an airframe that includes a Towed Platform.

In December of 2022, CFD simulations were initiated in an evolution to digital twin technology where the digital twin is used to identify prototype details and the performance of protypes are used to increase the accuracy of the digital twin.

It is projected that in the next nine months (3 months prior to a 6-month Phase I study), approximately 20 generations of prototypes will be built and tested at scales of 500 to 2000 grams. During these nine months, fabrication methods will be refined, digital twin technology will be made more accurate and include projections of performances of larger prototypes, and the amount of information gained from prototypes will be increased. In this era of light-weight and relatively low-cost electronics, it is possible to gain information from prototypes that approach and exceed information that previously required wind tunnel studies. The prototype aircraft consist of four components: a) 3-D Printed Coupling Devices, b) beams, c) sheets, and d) electronics.

The 3-D Printed Coupling Devices provide the following purposes and advantages:

- Rapid assembly/attachment of beam, sheets, and electronics into an RC aircraft.
- Easy modification designs through CAD generation of STL files in a format compatible with the 3D printer.
- Easy replication of the devices.
- Ease of ability to make complex and light weight components.

Within the CAD program, representations of the beams, sheets, and electronics can be assembled into a digital twin STL file on which CFD simulations can be performed. And within SimFlow the digital twin can be studied at different scales, speeds, freestream velocity vector angles, and configurations (i.e., positions of control surfaces).

Prototypes to date have used PLA filament, laminated plastic sheets, and bamboo structural components. With an increases budget made possible with SBIR funding, these components will evolve into increased use of Nylon and PET filaments with carbon composite sheets and structural components.

Preliminary Results – Hundreds of CFD simulations have been performed on thin plate cambered airfoils to identify performance trends. Figure 8 summarizes the impact of freestream velocity angles relative to the airfoil model. At 0°there is a prominent reverse lift at the leading edge with high pressure above the leading edge and lower pressure below the leading edge.

This reverse lift goes away at higher angles, but the combination of higher angles and higher camber lead to lower L/D. Optimum L/D have: a) a positive ΔP throughout the lower side, b) a negative ΔP throughout the upper side, and c) no more surfaces at higher pitch angles than necessary.

Especially when operating at lower lift pressures, subtle changes in the airfoil can transform the pressure profile along the entire airfoil. Figure 10 illustrates a horizontal flat plate airfoil where all the trailing edge taper is on the upper surface. In the absence of the taper, the upper and lower surface pressure profiles were identical. The takeaway is that the velocities and pressures created by a propulsor can change the entire pressure profile of a surface.

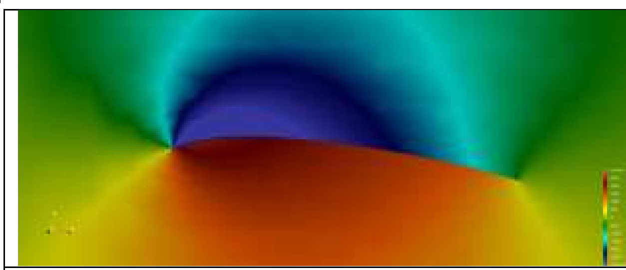

Figure 11. Example of pressure profile for 70 ***L/D*** performance.

Figure 11 illustrates the type of pressure profile that leads to L/D in excess of 70:1; a performance that is possible with thin-plate cambered airfoils. For this airfoil, the local ***L/D*** is equal to 57/AoA°, this is a geometric constraint related to how a pressure transforms to lift and drag forces on a surface; but the equation requires interpretation for negative AoA. To achieve ***L/D*** in excess of 70, the lift pressures need to be focused on the surfaces have AoA < 0.8° with at least some negative AoA to create induced thrust.

Figure 10. Horizontal flat plate airfoil with upper surface taper on trailing edge.

Equation 1 implicitly relates ***L/D*** to the aspect ratio ("AR"). At low aspect ratio, Equation 2 predicts that ***L/D*** becomes increasingly low. Wingtip vortex mitigation does not correct this, because at low aspect ratios a trailing edge vortex can transform an otherwise highly efficient pressure profile to a reverse lift at the leading edge. Strategic placement of a propulsor interferes with the trailing edge vortex with a reversion back to desired pressure profiles.

$$C_{di} = \frac{C_l^2}{\pi AR\ e} \quad (2)$$

Since aerodynamic lift is not a "work" process (i.e., the force does not go through a distance for the lift component of the force), a propulsor is able to help shape the pressure profile about a surface with zero to minimal addition work beyond that needed for propulsion.

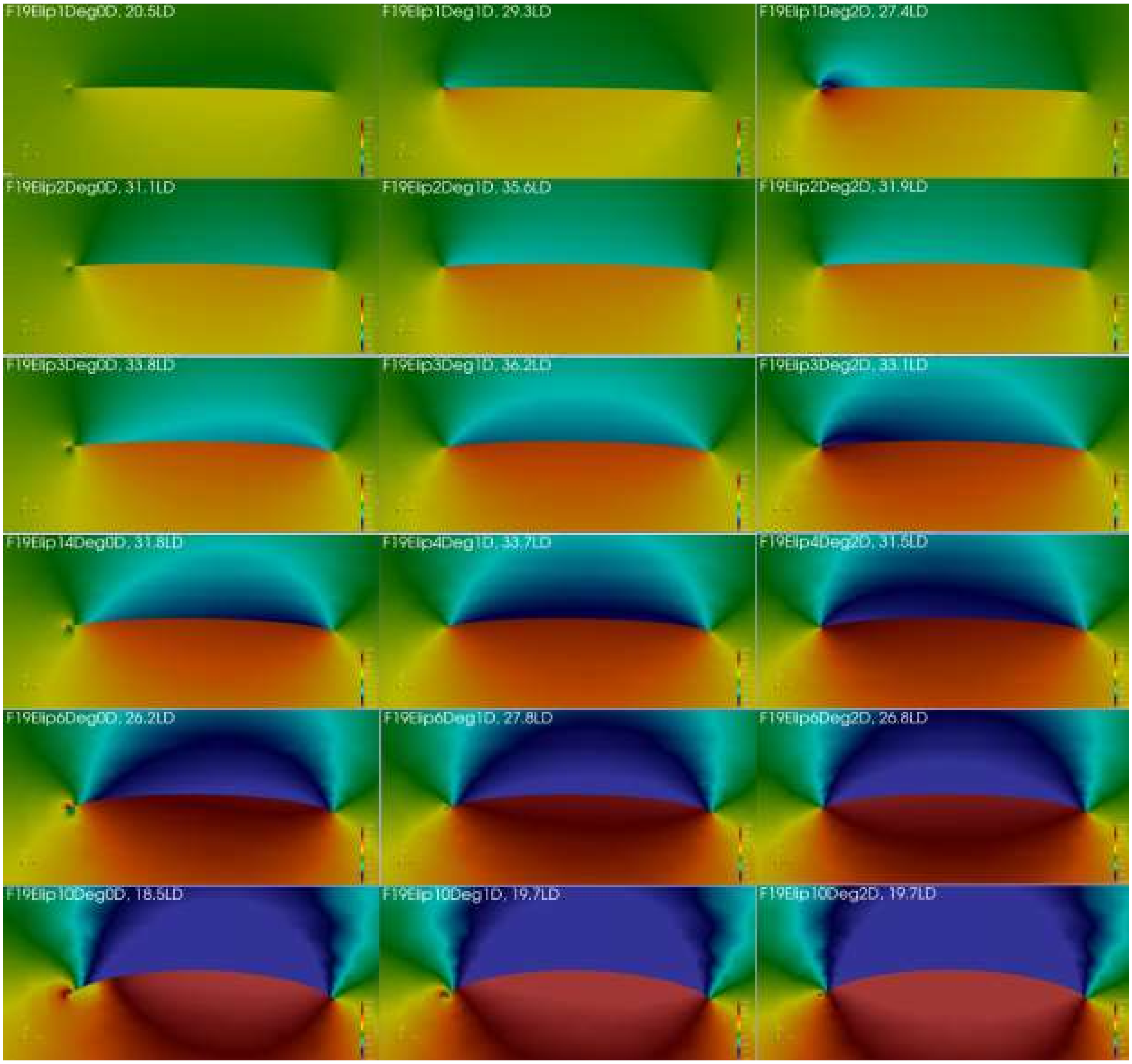

Figure 9. Summary of pressure profiles from CFD studies on elliptic cambered airfoil with similar increased camber at leading and trailing edges. The maximum camber was varied (increasing from top to bottom on figure, at values of 0, 1, 2, 3, 4, 6 and 10) as was the freestream velocity vector angles relative to the airfoil (horizontally, at values of 0, 1, and 2).

Engineering Aerodynamic Lift - Three degrees of freedom allow L/D to be optimized for a given sheet thickness: overall camber, a trailing edge taper to a sharp edge, and freestream velocity angles:

1. Increased fraction of <u>camber near the leading edge</u>,
2. Increased fraction of <u>camber near the trailing edge, and</u>
3. Shape of the leading edge.

These three degrees of freedom are coupled, and can be tuned to create a uniform lower pressure region above the airfoil and higher-pressure profile below the airfoil.

The engineering of a thin-plate cambered airfoil can be engineered/shaped to provide desired pressure profiles. At low ***AR***, propulsor location, fences, and serrated trailing edges are needed; and the surface of the airfoil will need to be tailored to those conditions to optimize *L/D*.

Part 5: Related R/R&D

Intellectual Property Management – Patents and pending patents on or related to the Towed Platform include the following:

- US11,186367, US10,589,838
- PCT/US20/36936 (EPO nationalized),
- PCT/US21/16392 (US, India, Australia, Canada, South Africa),
- PCT/US22/014884.

In-hand patents, PCT International Search Reports, and PCT Article 34 Examinations verify a good and broad base of patent protection. Use of the towed platform for commercial gain or for second-party-funded R&D would be subject to prosecution in each of the above-listed countries.

A series of papers (currently 3) have been drafted with sufficient CFD results to validate significant contributions to the science. These three papers and a book proposal will be complete for submission by mid-April, 2023.

There is a long history of studying both flat-plate airfoils and cambered airfoils as test cases and comparisons for new airfoil designs. Flat-plate airfoils are an interesting test case, as shown in this paper, but ultimately lack stability and optimal performance over a range of air-angle-of-attacks. Cambered airfoils show promise for maintaining good lift. The magnitude of lift of cambered airfoils is highly susceptible to the extent of camber. Scanning a range of high camber airfoils, Milgram identifies that large cambers, around 8%, have significantly more drag than lower cambered airfoils at high angles of attack caused by a poor pressure build up, though they can reach upwards to 30 L/D (Milgram, 1971). Similar, a compilation of data on many airfoils by Selig identifies that cambered airfoils have a higher total C_l potential than many other modern airfoils, while ultimately on these wings fail as the angle of attack and flow increases, the drag reduces the total L/D potential compared to traditional airfoils in their times (Selig, Michael S. Guglielmo, James J. Broeren, Andy P. Ggiuere, Philippe, 1995). The optimal camber for increasing lift without overly inducing drag has been identified at around 4-6% camber of the wing (Traub & Coffman, 2019; Winslow, Otsuka, Govindarajan, & Chopra, 2017). These compilations suggest that there is significant potential for an optimal design of thin, cambered airfoils to make breakthroughs in energy efficiency.

The introduction and development of computational fluid dynamics has removed many of the challenges for optimization of airfoil designs and provides potential for understanding the fundamental mechanics of lift. A significant challenge of airfoil design and functionality is the development of flow instabilities and vortexes and lamination separation bubbles. The use of wind tunnels has allowed these phenomena to be well studied and documented through the use of techniques such as particle image velocimetry (PIV) (Burgmann, S. Dannemann, J. & Schroder, W., 2007), which defined and identified pressure and vortex instabilities as they worked their way up the pressure side of the wing. This has led to the extensive study and definition of instabilities and flow behaviors on wings (Klose, Spedding, & Jacobs, 2021). These pressure distributions are impacted more from the Reynold's number and flow rate than the turbulence experienced on the wing (Michna & Rogowski, 2022). Therefore, an argument that airfoil design around pressure distribution would be the optimal method to improve airfoil efficiency, which this study aims to complete by studying sample cases of flat-plate and thin-cambered airfoils.

Using computational fluid dynamics, many new and interesting cambered airfoils have been developed in similar literature, proving their potential. Osei has developed a cambered airfoil with the potential of reaching and L/D up to 135, with theoretical L/D maximum listed around 155 for cambered airfoils (Osei, Emmanuel Yeboah, Opoku, Richard, Sunnu, Albert K. Adaramola, Muyiwa S., 2020). 2D simulations are able to be used for as an appropriate numerical method for lower Reynold's number, with 3-dimensional analysis need when more accurate qualitative characteristics are needed (Lee, Nonomura, Oyama, & Fujii, 2015). There is significant potential for the use of learning algorithms to adjust and optimize the shape of airfoils based on results from CFD results (Achour, Sung, Pinon, & Mavris, 2020-01-06). Through the development and testing of airfoils with morphing trailing edges, Wu is able to identify how minor differences in developing similar shapes has a noticeable impact on L/D in both physical and computational experiments, reaching theoretical L/Ds of 80 by minor adjustments to how the trailing edge is structured which determines how the pressure propagated from the rear of the airfoil forward (Wu, Soutis, Zhong, & Filippone, 2016).

Battery Weight Issue –HAPS/HALE prototypes have overcome the battery weight issue to sustain 24/7 flight by storing potential energy in the form of altitude during the day with gliding at night as a key component of current 24/7 flight. SP-Drone's increased efficiency and large solar panel surface areas makes solar power possible for most aircraft applications with current battery technology. Even extended night time flight markets can be taken over with the following technologies: a) improved hydrogen storage, b) lighter-weight batteries, c) energy beam or umbilical cord energy transfer and d) replacing structural components with batteries (or hydrogen tanks) that provide both structure and energy storage. HS-Drone will provide a market stimulus to advance these other important technologies (broader impact).

Power Ratio of Towed Platform – Herein, the Power Ratio is a measure of how much power a Towed Platform can deliver to a lead aircraft. In principle, a Towed Platform can perform as a scalable power supply that enables any aircraft of any scale to fly under solar power, including 24/7 flight.

The Power Ratio is defined as the ratio of power produced to the ratio of power needed for flight and is provided by the following equation.

$$Power\ Ratio = \frac{P_{PV}}{g\ (D/eL)\ U} \qquad (3)$$

Where: $\boldsymbol{g}$ = 9.8 m/s^2,

$\boldsymbol{P_{PV}}$ is power density of photovoltaic array including wing weight (W/kg).

$\boldsymbol{U}$ is velocity (m/s) with benchmarks of 343 for sound and 250 for commercial airliner.

D/L is reciprocal of lift-drag ratio for Aspect Ratio = ∞,

$\boldsymbol{e}$ is an efficiency factor associated with low Aspect Ratio form (target of 0.5).

Tables 3, 4, and 5 provided compiled data used to estimate the performance available from commercial products for solar power collection and wing construction. Based on these summaries, a reasonable value for Photovoltaic cell productivity above the clouds is: 30% * 120% * 200 W/m^2, or 72 W/m^2. For a square meter, 72 Watts is provided at a weight of 0.24 kg photovoltaic array and 0.114 kg of wing membrane, or 72 W per 0.354 kg (203 W/kg).

To attain jet speeds on a commodity-grade panel would require an L/D (AR=∞) of 24 [9.8(m/s^2) * 250(m/s) / 0.5 / 203(W/kg)]. The infinite AR performance is the 2D airfoil performance which is typically reported for airfoils.

Table 3. Properties of photovoltaic panels.

Property	Value	Source (comment)
Power Density (W/kg)	150	https://www.spectrolab.com/photovoltaics.html (honeycomb)
	1000	https://www.spectrolab.com/photovoltaics.html (thin film, expensive)
Efficiency	30%	Microlink web page
	22%	Sunpoercorp.com
	30%-32%	https://www.spectrolab.com/photovoltaics.html
	40%	https://www.spectrolab.com/photovoltaics.html
Surface Weight (g/m^2)	350	Microlink web page
Sun Radiation (W/kg)	100-230	(Smil, 2010) from cloudy locations to desert locations.
	120%	(Smil, 2010) without atmospheric interference

Table 4. Properties of solar-powered aircraft.

Property	Value	Source (comment)
Mass per Area (kg/m^2)	1	Bravo, 2019 (9.5m span, 1.05m chord, 8.16 kg)
	3.9	Hanson, 2023 (140 kg per 36 m^2)
	0.58	Wikipedia, Nasa Pathfinder (for Pathfinder Plus)
	0.45	Wikipedia, Nasa Pathfinder (for Helios HP03)
	2.1	Agoes, 2021.

Table 5. Towed Platform mass breakdown for $10m^2$. (Bravo, 2019)

Element	Contemporary Wing (kg)	Towed Platform (kg)
Ribs	0.22	0.18
Spars	1.09	0.55
Skin	0.82	0.41
Boom	0.15	N/A
Total	2.28 kg (0.228 kg/m^2)	1.14 kg (0.114 kg/m^2)

These estimates show that jet speeds (250 m/s) are attainable with electric propulsion. In fact, cambered airfoils are able to achieve >4x the identified ***L/D*** = 24. Table 6 summarizes factors that impact viability and evolution where factors less than 1.0 detract from viability.

Table 6. Factor corrections to base case estimate of minimum 2D ***L/D*** =24.

Factor	**Property and Comment**
0.4-0.7	For 24/7 operation with energy storage (e.g., altitude) to traverse the night. 24/7 operation does allow traveling against Earth's rotation during night.
<0.75	Calculation is only for Towed Platform. At a minimal, a propulsion system, control system, and some batteries need to be included.
0.85	Shaft Work Reported – Conversion to propulsion work must be included.
>1.33	When 40% photovoltaic cell efficiency becomes commodity. Also includes reductions in weight of photovoltaic cells.
>2	A velocities of 250 m/s is cruising speed for airliners, many good applications exist at 125 m/s and less.
2-4	With a target of thin-plate cambered airfoils at 50 < ***L/D*** < 100.

Conclusions to be drawn from Table 6 include:

- Low velocities make 24/7 solar flight rudimentary, as is the case with the burgeoning HAPS/HALE prototypes.
- Moderate velocities of 140-280 mph (67.5-125 m/s) are viable and provide excellent performance for many transport markets.
- Battery weight is an issue, but this can be overcome if energy can be stored in altitude (e.g. 90,000 ft) and for flights above the clouds during day times.
- Improved photovoltaic cells will reduce costs and increase capabilities.
- High L/D are key to immediate upside potential for high-speed applications.

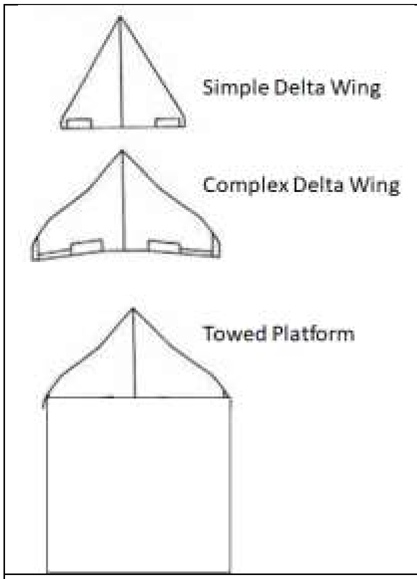

Figure 12. Best options for high surface area aircraft.

A remaining issue resides in the ability to deploy the high surface areas of solar panels in high-speed applications. Rectangular wings of high aspect ratio, as are common with HAPS/HALE airframes, can be ruled out due to lack of structural strength to handle high speeds. A key factor in the consideration is the large surface areas that are required. Whereas airliners will often have wing loadings of 100 lb/ft^2, solar aircraft may have wing loadings as low as 0.5 lb/ft^2. Optimal high speed solar aircraft will likely have a 20X to 40X increase in wing surface area (on a payload basis) relative to contemporary aircraft. Figure 12 compares the three most-viable options to meet this large surface area. Three factors stand out as favoring the Towed Platform approach:

- It provides the least-expensive surface area, that being a single sheet in a longitudinally flexible platform.
- It provides the lowest kg/m^2.
- It provides half the wingspan, improving landing options.

- It provides possible in-flight solar cell deployment options.

Two key questions are coupled with the research objective of this project. How much can L/D losses be mitigated for the low aspect ratio design of Towed Platform airframes? How low-cost can these aircraft be?

Cost of Solar Power – A 2019 breakdown of solar power costs is provided by Figure 13 (6.8 cents per kWh for U.S). These costs show that about a third of these costs are the modules and inverter (2.3 cents), the other two thirds of the cost would be associated with aircraft construction. The following characteristics would lead to reductions in these costs:

- 20% more radiation at higher altitudes (1.2X).
- Up to 130% more radiation above the clouds (2.3X).
- Scheduling that goes against Earth's rotation at night (1.5X).
- Improved ability to orient panels (1.5X).
- Lowered costs in place and expected since 2019 at 50% lower (2X).
- Credit for mass production of racking/mounting at factory installed on Towed Platforms; this credit is for the panel as a ready-to-go thin-plate cambered wing which substantially reduces aircraft manufacturing costs (2X).

Each characteristic includes a factor of improvement in power per cost. The cumulative factor is 25X; or 2.3 cents/kWh divided by 25.

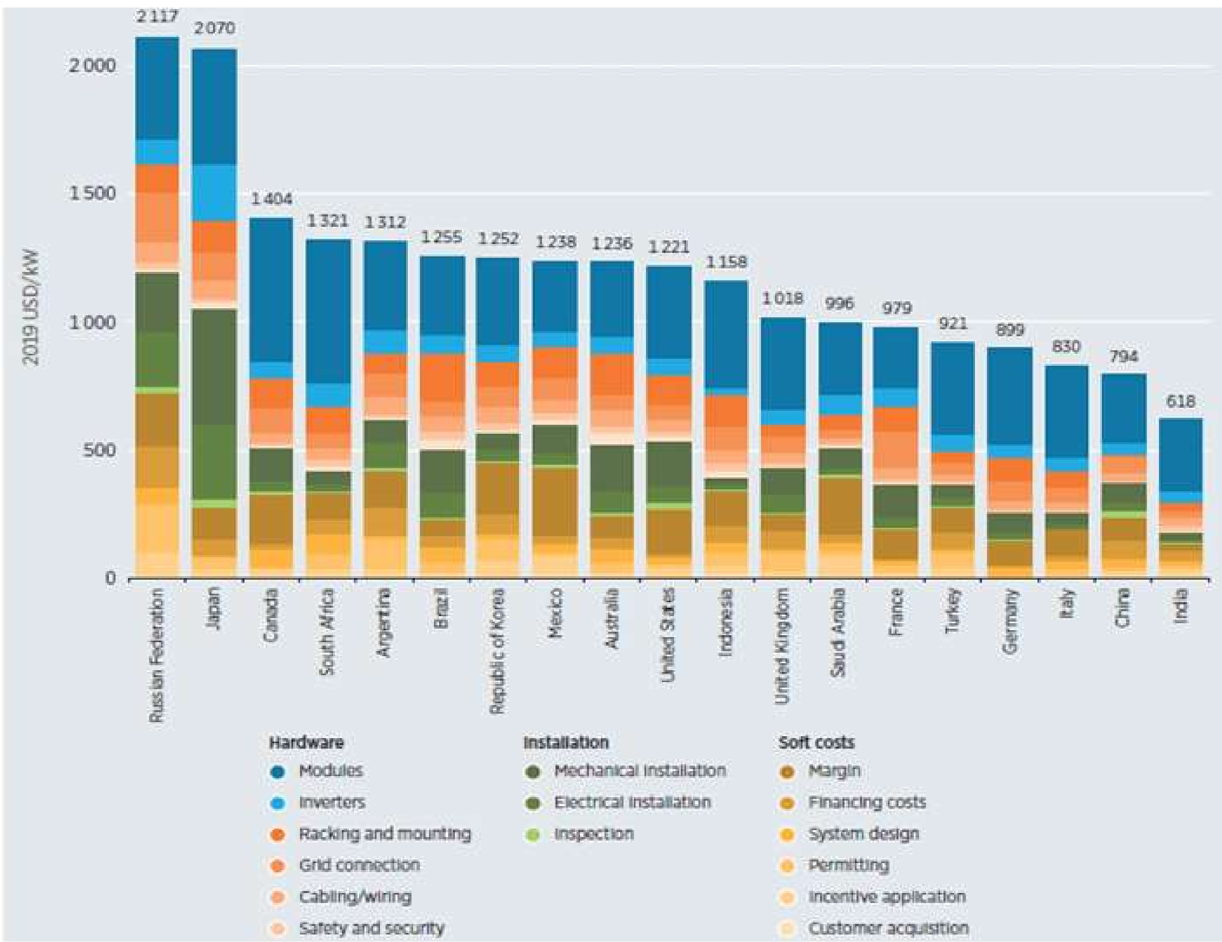

Figure 13. Detailed breakdown of utility-scale solar PV total installed costs by country 2019. U.S. costs were 6.8 cents per kWh. (https://ratedpower.com/blog/solar-farm-costs/).

There is clearly the opportunity to have aircraft having costs of 1-2 cents/kWh by 2027 (seven years after the 2019 costs of Figure 13) for applications with regularly scheduled service, such as: delivery, solar refueler, and passenger aircraft. This is a near-zero emission technology in competition with jet fuel which costs more than 18 cents/kWh.

Towed Platform technology (as part of SP-Drone technology) has an unprecedented capacity to both reduce costs and reduce emissions (including greenhouse gas) while improving national security and quality of life. The technology and trends are so overwhelming that it is less about the technology than it is about intelligence, lack of conflict of interests, and leadership.

Part 6: Key Personnel and Bibliography of Directly Related Work

The Phase I Team includes:

- G.J. Suppes (PhD, P.E.) who is the company founder and proposal PI.
- A.B. Suppes (PhD) who performs CFD studies.

G. Suppes (“PI”) has a BS in chemical engineering (Kansas State University) and PhD (The Johns Hopkins University) in Engineering with about 120 refereed publications having over 6,000 citations. While the company was founded in 2007, Dr. Suppes has only been working full time in the company since May of 2017. This would be the PI's first Phase I SBIR. A. Suppes has a BS in Chemical Engineering from The Johns Hopkins University and a PhD in Chemical Engineering from UPenn.

The PI’s publications include topics of: energy analysis/technology, lifting body technology, polymers/composites, and online education. The PI has taught multiple courses on energy technology, batteries/fuel cells, polymer science, fluid dynamics, design methodology, process control/modeling, and computer programming. Computer programming courses have included multiple programming languages as well as simulation and PID control programs/equipment.

That history includes the PI being the advisor (with funding) for sixteen PhD graduates on topics of energy technologies and polyurethane engineering; all PhD advisees included wet lab studies/experiments from labs that were maintained by the PI for 25 years. 45 years of experience in fabrication (including trouble shooting) started at age 11 with operation and repair of combine harvesters as well as a range of other equipment/electronics starting a couple years later. The PI's combination of experience in energy analysis, material science, fluid dynamics, and controls is a good combination to lead this project.

The PI writes and prosecutes patents for the Trust with over 30 years of experience in writing and prosecuting patents. A. Suppes’ PhD studies were intensive in fluid dynamics, and he performs computational fluid dynamics (“CFD”). Three papers are in preparation on SimFlow CFD studies toward a better understanding of thin-plate cambered airfoils.

The vitae of the PI is provided on the next page.

Part 7: The Market Opportunity

This project is on a breakthrough aerial platform that can deliver L/D in excess of 50:1 in a high-speed format with large areas for photovoltaic cells. The design may be used for fully solar-powered aircraft or for aircraft having power augmented by solar power.

Also, the design is inexpensive, with most of the planform area comprised of single-sheet construction. The approaches (and pending patents) apply to fuselage designs, with an emphasis on induced thrust. The market includes the following:

The technology sectors directly impact are:

- Air transit ($800 billion, annually for passenger with jet fuel at 12% of liquid fuels; Total transit industry estimated at about $5 trillion.)
- Rail/Bus/Truck/Ship/Barge Transit
- [Air] Taxi Transit
- Communications and Internet Technology, HAPS/HALE ($5.2 trillion for internet, $1.7 trillion telecom market)
- Other Satellite Technologies (HAPS/HALE)
- Space Access
- DOD (weapons, transit, reconnaissance, drones} ($0.45 trillion for global defense market)
- Energy (solar energy harvesting, $6 trillion for global utilities market)

VITAE
Galen J. Suppes, PhD, PE

EDUCATION:

The Johns Hopkins University,	Doctorate of Philosophy Engineering	Ph.D., 1989
Kansas State University,	Chemical Engineering	B.S., 1985
Swiss Federal Tech. Inst.	Exchange Student	10/83-8/84
University of Houston	Post-Doc Course Work	8/91-5/92

PROFESSIONAL EMPHASIS & PASSION (Fall, 2022):

Extraordinary opportunities exist for significant advances in aircraft flight efficiency (i.e., lift-to-drag ratios); those opportunities include basic advances in airfoils (i.e., airfoil superstructures). The technology can make most of today's military and transportation infrastructure obsolete in a few years and will bring in an era of low-cost and fully renewable transportation and industries. That technology enables advances on other topics such as electric-fuel hybrid jet engines (only viable with high speed solar aircraft). The following are patents of the Applicant on these topics:

Provisionals	Airfoil Superstructure (2022, 2023)
PCT/US21/16392	Flat Plate Airfoil Platform Vehicle
PCT/US20/36936	Multicopter with Improved Propulsor and Failsafe Operation
PCT/US22/14884	Hybrid Engine and Aircraft Application
US 17/591034	Hybrid Engine and Aircraft Application
US 11,186367	Multicopter with Improved Propulsor and Failsafe Operation
US 10,589,838	Multicopter with Passively-Adjusting Tiltwing

PROFESSIONAL EXPERIENCE:

6/17-present	CEO, Homeland Technologies, LLC.
8/01-5/17	Professor, J.C. Dowell Professorship (and other ranks), Chemical Engineering, MU.
8/92-8/01	Associate/Assistant Professor, Chemical and Petroleum Engineering, Univ. of Kans.
1/89-7/92	Senior Research Engineer, Polyurethanes Process Research, Dow Chem., TX.

AWARDS AND HONORS:

>6,000 Citation – of Applicant's peer-refereed papers.

FELLOW – American Institute of Chemical Engineers (AICHE)

Registered Professional Engineer – Missouri, Kansas (not renewed), Texas (not renewed).

2006 Presidential Green Chemistry Challenge Award - Presented at the 2006 ACS 10th Annual Green Chemistry and Engineering Conf., Academy of Sciences Building.

(Invited Speaker)* 2006 Gordon Conference (Green Chemistry), Oxford University.

(Invited Plenary Speaker)* 2014 The Seventh Tokyo Conference on Advanced Catalytic Science and Technology (TOCAT7), June 1-6, 2014, Kyoto, Japan.

PhD ADVISEES – 16

MS ADVISEES - 31

BOOKS: 6, including:

<u>Sustainable Power Technologies and Infrastructure.</u> Applicant and T. S. Storvick. Academic Press Sustainable World Series, Elsevier Press, Boston, 2016.

PATENTS: >25 granted

PUBLICATIONS: >125 refereed publications, including:

3D Urethane-Enhanced 3D Printing for Product Scaleup and Market Development Production, CPI Conference (2021), Denver, CO, October 5-7, 2021.

Simulation as a tool for biopolymers design. Science (Washington, DC, U S). 2014;346:1055-6.

VITAE
Adam Suppes PhD

Education & Research Experience

Aerodynamic Computational Fluid Dynamcs — Chicago, IL
Part-time researcher — Jan-Present 2023
Computational fluid dynamics and literature search to assist in improved airfoil design.

University of Pennsylvania — Philadelphia, PA
PhD, Chemical and Biomolecular Engineering — 2016-2022

Dissertation: The Effect of Confinement on T-Lymphocyte Upstream Migration Under Shear Flow
Projects: *in vitro* T-cell adhesion and motility under shear flow, cell culture, microfluidics, patterned protein microcontact printing, and oversight of undergraduate research on KG1a migration under flow.
GPA 3.97. Advisor: Prof. Daniel A. Hammer. — December 22, 2022

The Johns Hopkins University — Baltimore, MD
B.S. Chemical and Biomolecular Engineering — 2013-2016
Minor: Spanish Language and Hispanic Culture

Undergraduate Researcher Projects: MDA-MB-231 (breast cancer cell line) migration under confinement and development of stiffness tunable Hydrogel HEMICA devices for cell migration research.
GPA 3.96 Advisor: Prof. Konstantopoulos

Hickman High School — Columbia, MO
GPA: 4.0. Valedictorian — 2013

Fluid Dynamics	SimFlow and ParaView CFD Software
Soft lithography	Statistical Analysis
Technical training on Heidelberg 66+	Cellular Adhesion, Migration, and Culture
Microcontact Printing	Protein Purification
Microfluidics	Fluorescent Microscopy and Imaging
Surface Chemistry	Critical Thinking, problem solving, and
MATLAB	independent research

Selected Research Publications and Presentations

Suppes, Adam B. and Hammer, Daniel A. (*In Preparation)* Directional Migration of CD4+ T-cells Under Shear Flow in Microfluidic Devices

Suppes, Adam B. and Hammer, Daniel A. (*Under revision for Annals of Biomedical Engineering*) Directional Migration of CD4+ T-cells Under Shear Flow on Stripes of Adhesion Proteins

Suppes, Adam, and Hammer, Daniel A. BMES Poster Presentation. 2021. Direction of Migration of CD4+ T cells Under Shear Flow on ICAM-1 Depends on Width of the Pattern

Suppes, Adam, and Hammer, Daniel A. AICHE Oral Presentation. 2020. Effect of Patterning of ICAM-1 on the Upstream Migration of CD4+ T-Cells Under Shear Flow

Suppes, Adam, and Hammer, Daniel A. BMES Poster Presentation. 2019. Effect of Patterning of ICAM-1 on the Upstream Migration of CD4+ T Cells Under Shear Flow.

Afthinos, Alexandros, Zhao, Runchen, Suppes, Adam, Konstantopoulos, Konstantinos. BMES Oral Presentation. 2016. HEMICA-Hydrogel Encapsulated Micro-channel Array In Cancer Metastasis

The technology sectors indirectly impact are:

- Restaurant (food delivery)
- Online Shopping ($5.2 trillion, e-retail sales}
- Tourism (airborne cruise ships, improved access to lodges/cruise ships)
- Hydrogen Production/Delivery {solar powered production)
- Atmospheric Decarbonization
- Airborne Chemical Industries (e.g. ammonia production)

Global sales are identified for select markets in a manner to avoid overlap (e.g., liquid fuels market is considered included in transit market). That annual marker for the few where global sales have been identified total is $23.55 trillion per year, with an emphasis that this is an underestimate since only select industries were considered. Transit, communications, energy, and online shopping markets emerge at annual over $5 trillion per year, each.

Additionally, the applications include no-till and low-till agriculture where chemical treatment replaces tilling. Use of solar power to operate drones carrying chemicals can and will substantially replace the fuel used to power tractors. Drones are also able to selectively administer chemicals and reduce costs and environmental impact.

Part 8: Facilities/Equipment

Homeland Technologies uses facilities at 1230 Knightsbridge in Charlottesville VA and the Riviana Radio Control Club (RRCC) test facility. Facilities include:

a) metals/machine lab,
b) electronics lab,
c) fabrication (wood/plastic) lab, d) 400 ft2 wet lab, and
e) storage.

Fabrication and Assembly Facilities Machine shop facilities include metal mill, metal drill press, metal lathe, welder, 3D Printers, and range of other saws and planers for fabricating test cells as well as benches and machines for fabrication.

Remote Control Equipment and Testing Remote control testing equipment includes multiple transmitters and operational drones including drones with 3D printed fuselages and wings. Testing of drones is performed with a Spectrum DS6e transmitter and compatible receiver, actuators, and motors.

Equipment Wet lab facilities include a variety of metal/plastic fabricating tools and the following which are used on a routine basis for lab work (with software support): Multiple AC power supplies including Elenco Model XP-720 AC/DC Power Supply and Eaton DC1 Variable Frequency Power Supply (60-300 Hz, up to 230 VAC), Multimeters and Circuit Fabrication Equipment, Multiple 3D Printers, An Inert Atmosphere Glove Box, Vacuum Oven for Drying Electrode Mixes onto Current Collectors, A Full Spectrum Programmable Laser cutter, CNC Router-Mill, EZ-STAT Potentiastat/Galvistat, and a Ball Mill.

Part 9: Subcontractors and Consultants

This Phase I study has no subcontracts or consultants.

Part 10: Related, Essentially Equivalent, and Duplicate Proposals and Awards

There are no related or equivalent pending proposals. The diverse range of applications and possible applications are summarized by Figure 8.

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