Airborne Wind Energy Technology and Regulatory Gaps: A NASA Perspective

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NASA AWE Focus

- **NASA is actively working to help AWE developers in two areas**
  - **Coordination with FAA on future AWE airspace regulations**
  - **Research and Development test sites available to all AWE developers within controlled airspace**

- **Future NASA AWE technology focus**
  - **AWE systems engineering analysis and design**
  - **Aerodynamics analysis, design, and testing**
  - **Advanced structures and materials**
  - **Robust unmanned autonomous vehicle control systems**
  - **Dedicated fabrication and test facilities for AWE**

Airspace Issues

- **The airspace issue is one of the largest hurdles facing AWE in the both the U.S. and many other countries**

Airspace Issues

- "Build it and they will come"?……probably not , without parallel work on airspace regulations. Integrating into airspace regulations will be one of the greatest obstacles to AWE and should be considered a key design requirement, not something left for "others" to figure out.

- NASA is acting in partnership with AWE developers to help the Federal Aviation Administration understand the technology and work towards new NAS regulations for AWE.

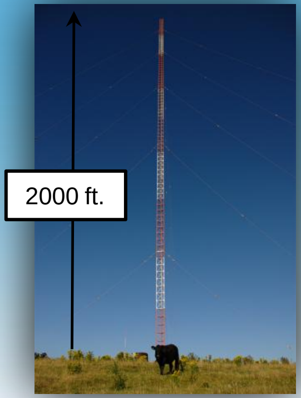
- Current airspace regulations in the U.S. and many other countries regarding tethered vehicles (kites and balloons) are restrictive, but are sufficient for sub-scale, low altitude testing. Part 101 is intended for hobby and sport, not for commercial activities.

  - *U.S. Code of Federal Regulations 14 Part 101 (U.S. Moored Balloons, Kites, Amateur Rockets and Unmanned Free Balloons*
    - No flight above 150 ft. (46 m) without NOTAM
    - Up to 500 ft. (152 m) with NOTAM
    - Waivers possible, but not intended for long-term commercial use
    - *Apparent* FAA position : Commercial AWE should not fall under a future addendum to Part 101.

Airspace Issues

- **Restricted Airspace**
  - **Not an option for operational commercial systems**
  - **NASA is working on identifying NASA restricted airspace sites for prototype testing**

- ***U.S. CFR 14 Part 77 Objects Affecting Navigable Airspace***
  - **Intended for static or semi-static objects (e.g. radio towers, buildings, cranes) up to 2000 ft. (610 m) with restrictions due to proximity to airports, etc.**
  - **Initial talks with FAA identify potential for low-altitude (<2000 ft.) AWE systems to fit into Part 77**
  - **Requirements for marking and lighting will impact AWE platforms.**
  - **Location approval is based upon proximity to airports and many other factors (including radar interference).**
  - **Use of land area is an important issue (radius of tether). Some AWE schemes do not score well on "Land use per kW-h" figure of merit, unless "dense operations" approaches are developed**
  - **Compliance with the National Environment Policy Act will be critical (i.e. avian/bat, visual, noise, and ground disturbance).**
  - **"A turbine on a (very) flexible tower"? - Is airworthiness certification required or is it not considered an aircraft under this regulation?**



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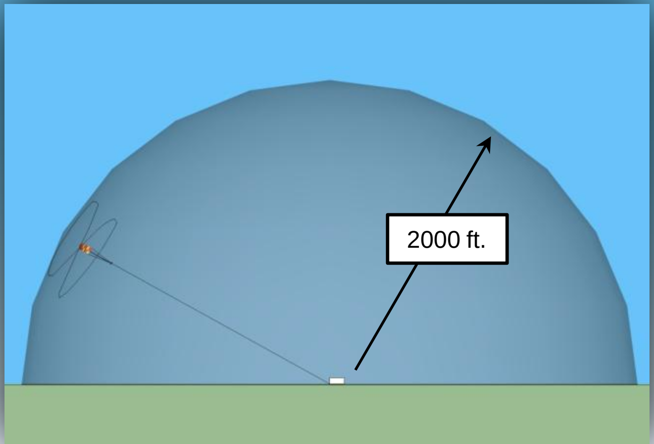

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Airspace Issues

- **Developing new regulations for AWE (i.e. a new Part to CFR 14)**
  - **The use of unmanned aircraft in the U.S. NAS remains limited despite years of work by the FAA and growing demand, because the existing methods for air traffic control are antiquated.**
  - **It will probably take many years (>10) of negotiation with stakeholders to develop new regulations for AWE . (consider current lack of new UAS airspace regulations as an example).**
  - **Consensus based standards through the ASTM might be another approach to consider for the industry in cooperation with the FAA (consider Light Sport Aircraft airworthiness as an example).**
  - **NextGen airspace system – What are the new technologies and how might AWE make use of them to fit into the NAS? Projected date of deployment is 2025.**

Airspace Issues

➢ **Developing new regulations for AWE (i.e. a new Part to CFR 14) (continued)**

- **Privatization of airspace would be in direct conflict with FAAs future vision and intent.**
  - **Above 2000 ft (610 m) will automatically be considered a hazard to navigation, and an impediment that burdens other air traffic for the gain of a single entity.**
  - **The only viable AWE technologies are those that enable shared use of the airspace.**
- **The first (small) step for AWE in the U.S. may be a new regulation similar to Advisory Circular 91-57 (Model Aircraft Operating Standards) for commercial use below 400 feet (122 m).**

"Methods and systems are expected to be developed that will allow UAS operations in the NAS with no negative impact on other operations (e.g., improved sense and avoid capability will help ensure safe UAS operations) " – National Aeronautics Research Development Plan 2010

Airspace Issues

- **International waters – International Civil Aviation Organization (ICAO)**
  - **Very little air traffic below 5000 ft. beyond 12 nautical miles (22 km) offshore**
  - **Wind conditions are better than over land**
  - **Some rescue aircraft, oil platform service aircraft and surface ship traffic**
  - **If ship-based (even if anchored), the United Nations Convention on the Law of the Sea (UNCLOS) applies**
    - **Class G airspace <2500 ft. (800m), VFR applies, NOTAM recommended**
    - **Coordination with ICAO probably required**
  - **Requires a new design approach for many companies**
    - **Over water**
    - **Extreme weather**
    - **Floating surface station**
    - **Sea-borne operations and maintenance**
    - **Transmission of energy vs. storage/transport of energy**

Image: Dr. J. Breukels, ASSET, TU Delft

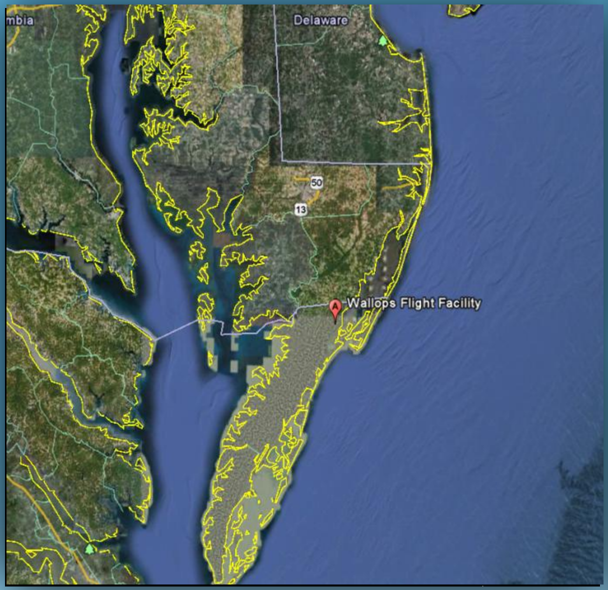
Near Term Testing in Restricted Airspace

- **NASA has several sites with restricted airspace (U.S. Government authorized use only) which can be used for research and development of AWE systems**
  - **Unlimited altitude**
  - **Open to all developers**
  - **Opportunity for third-party observation and sharing of information to bridge credibility gaps with investors and other stakeholders**

- **Potential test sites**
  - **NASA Wallops Flight Facility , Virginia**
  - **NASA Kennedy Space Center, Florida**

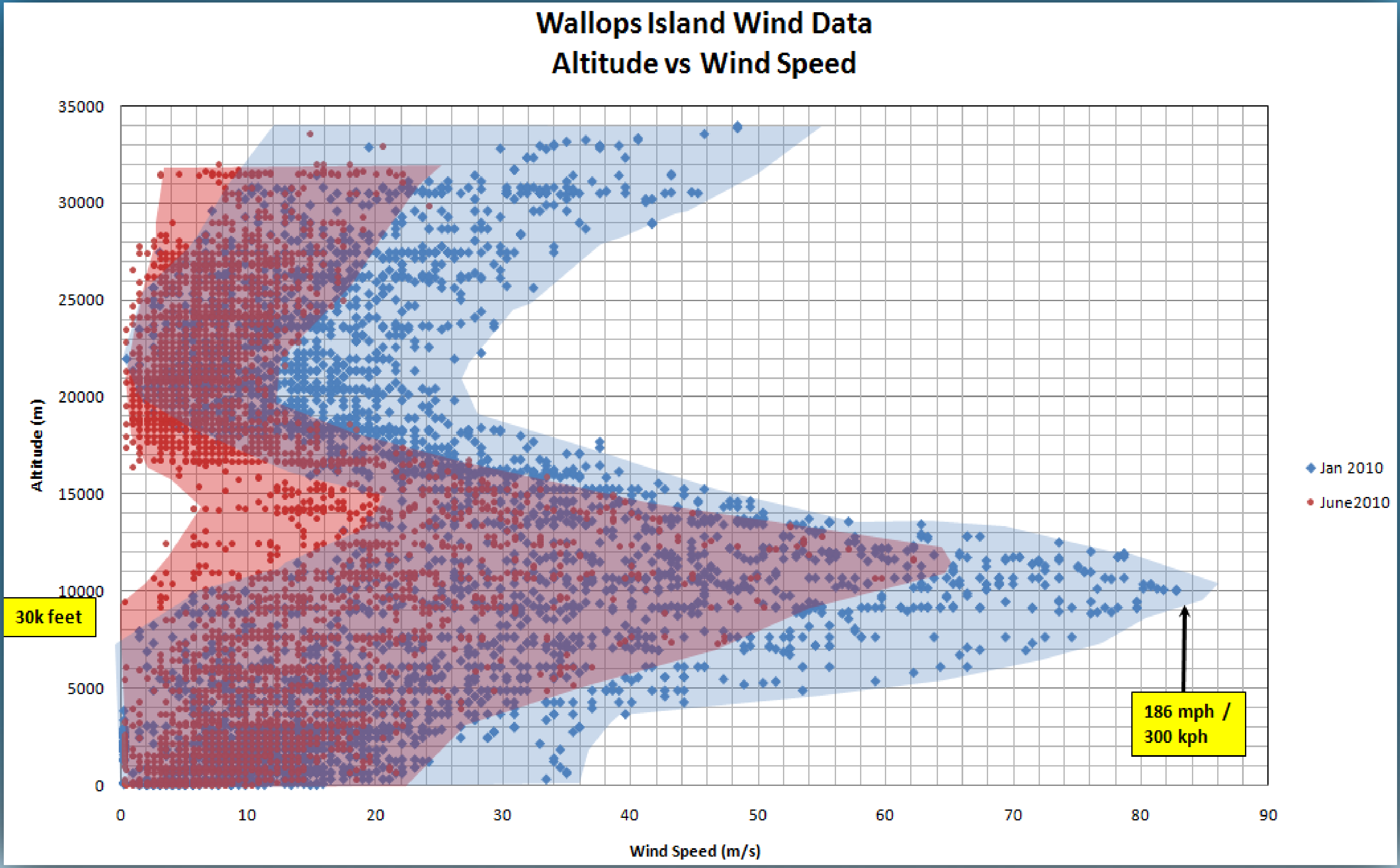
Near Term Testing in Restricted Airspace

- **NASA Wallops Flight Facility, Virginia (U.S. east coast)**
  - ➢ **Wallops has an existing capability for UAS testing in restricted airspace**
  - ➢ **750 ft. UAS runway**
  - ➢ **Very good wind conditions with very high percentage of available test days**
  - ➢ **Planning is underway with WFF officials and safety organizations**



Near Term Testing in Restricted Airspace

- Wind data from NASA Wallops Flight Facility

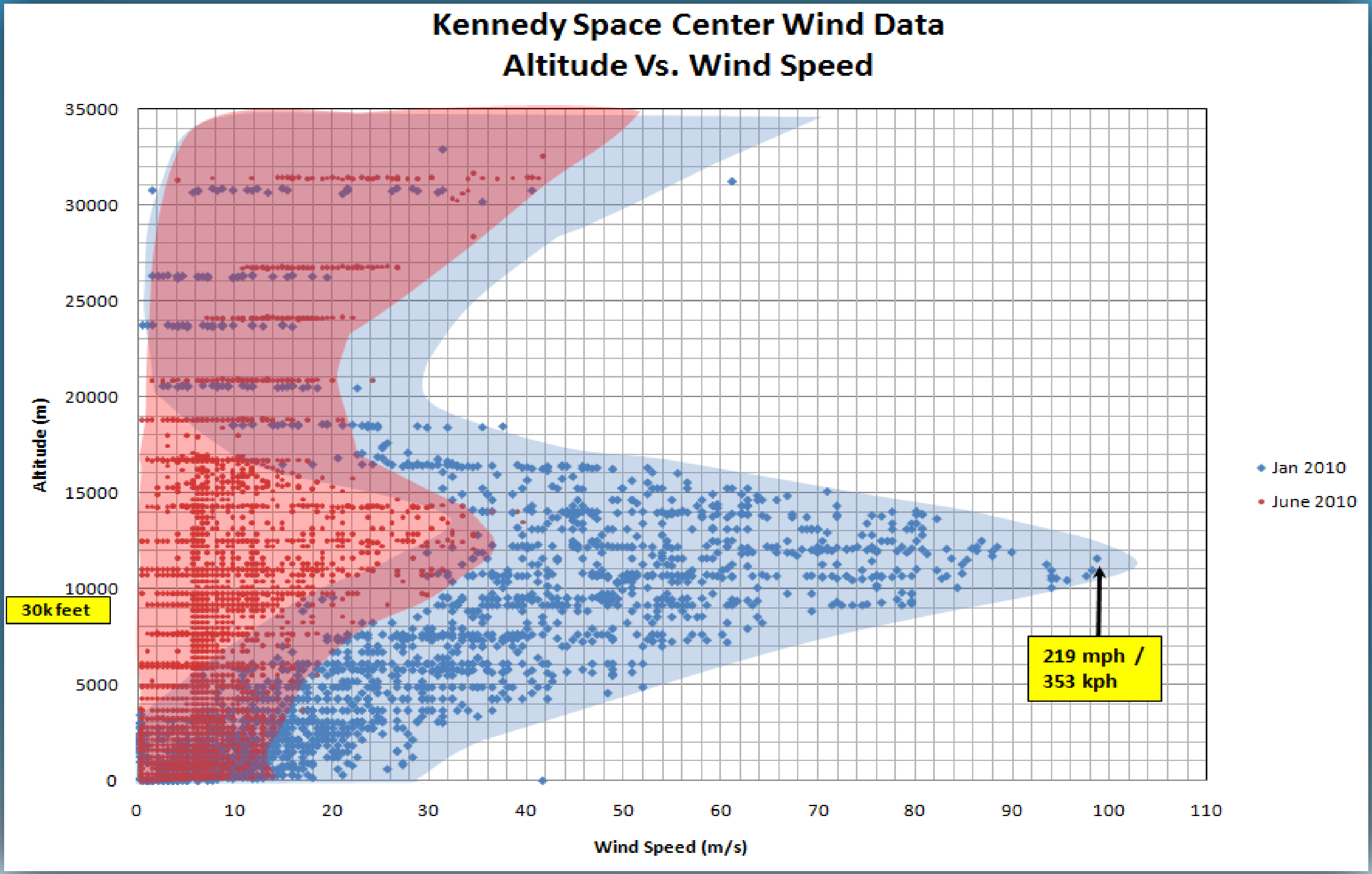


Near Term Testing in Restricted Airspace

- NASA Kennedy Space Center, Florida

Near Term Testing in Restricted Airspace

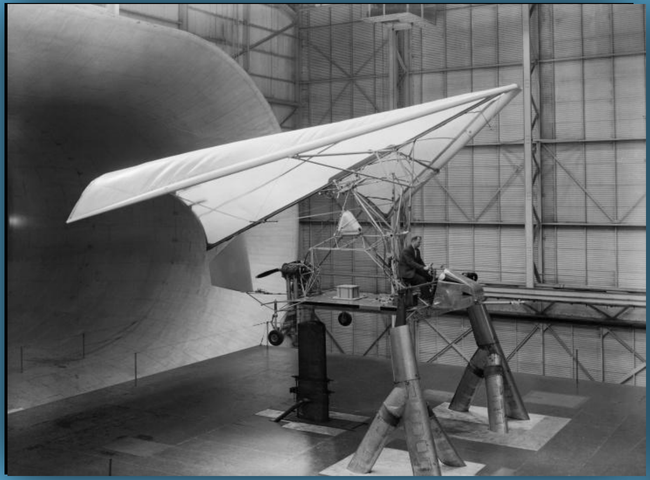
- Wind data from NASA Kennedy Space Center

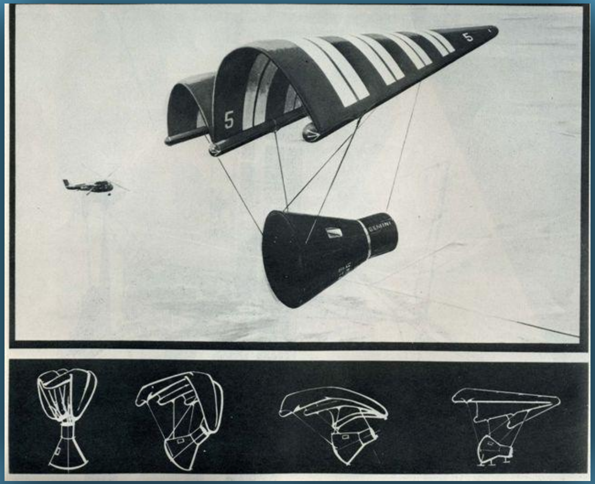


NASA Research Capabilities for AWE

Technology Gap: High performance, light weight, low cost kites for AWE

- **Aeronautics – Kites, Parafoils, & Parachutes**
  - ➢ **NASA has a rich history of kite and fabric aero device research (Rogallo, etc.)**
  - ➢ **NASA expertise will be brought to bear on improving aerodynamics, control, manufacturing, and durability**





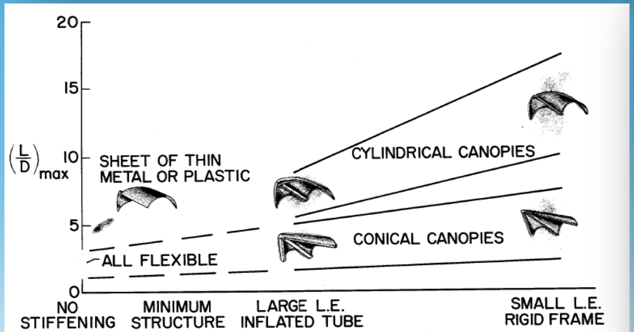
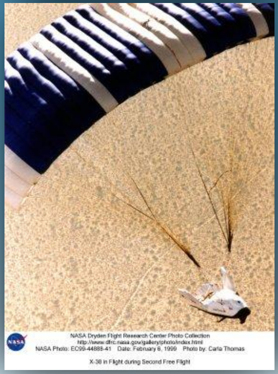


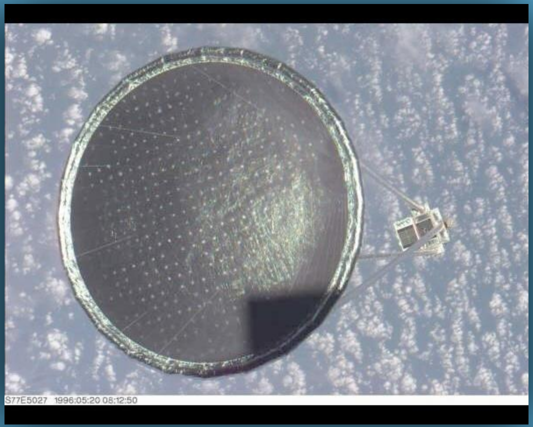
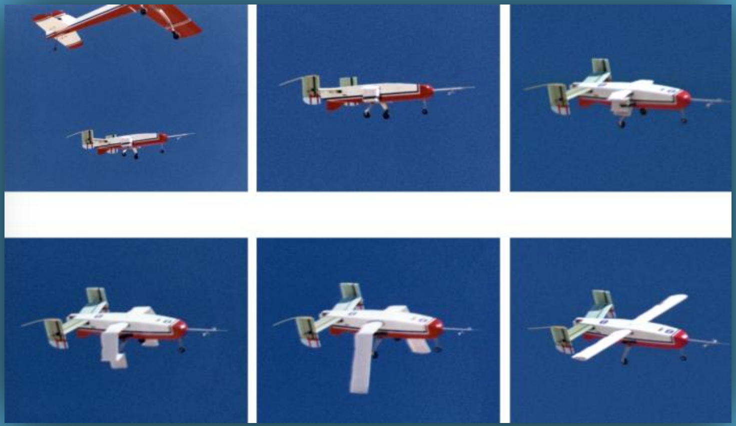
Figure 2.- Spectrum of flexible wings investigated and maximum lift-drag ratios obtained in wind-tunnel tests.

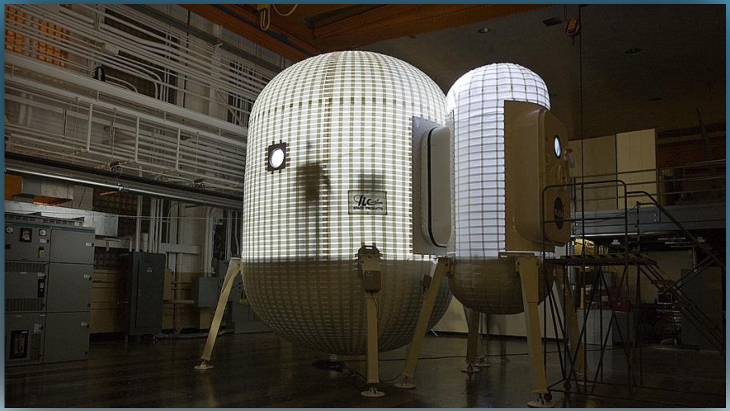


NASA Research Capabilities for AWE

Technology Gap: High performance, light weight, low cost inflatables for AWE

- **Inflatables**
  - **Inflatable structures projects at NASA present an opportunity for "cross pollination" between space-based inflatables and AWE**
  - **Close relationships exist with companies that design and manufacture inflatables**

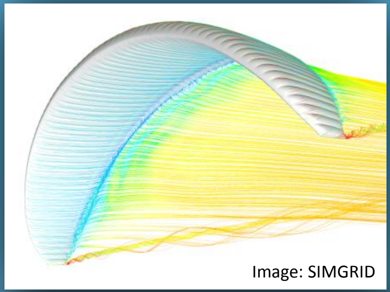




NASA Research Capabilities for AWE

Technology Gap: High performance, light weight, low cost airfoils and tethers for AWE

- **Current surf kite aerodynamics and construction techniques could be improved significantly**
  - **Current L/D of 3-5 for LEI surf kites could potentially be improved to 8-10 resulting in significant gains in power output per surface area and material used**
  - **Other construction techniques (beyond labor intensive sewn fabric) for low-cost, durarble construction need to be explored**
    - **Plastic blow molding with fiber reinforcement**
    - **Mass production capable fiber reinforced foam wings**
  - **Tether drag reduction needs experimental focus to produce a practical solution**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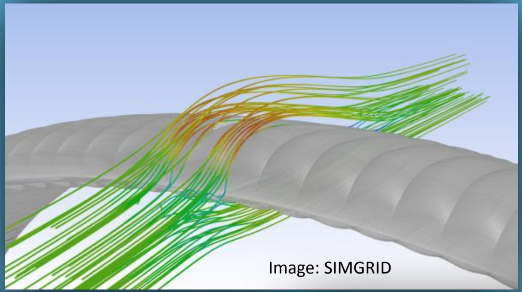
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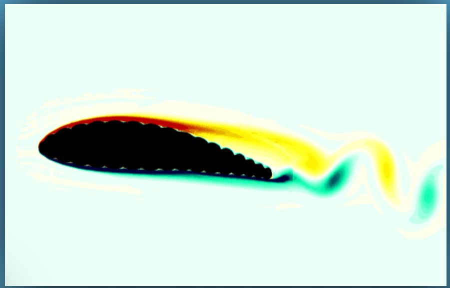



Image: WindLift

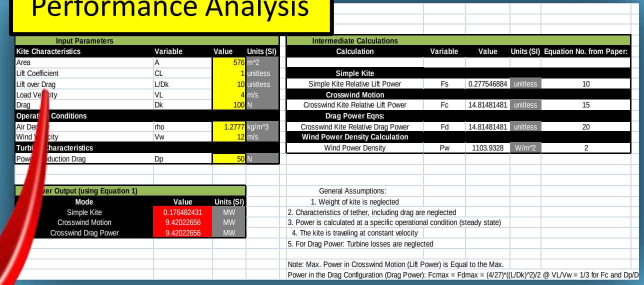
NASA Research Capabilities for AWE

Technology Gap: Integrated systems analysis

- **Systems Analysis and Concept Development**
  - ➢ **System level analysis & design tools exist that can readily be adapted to AWE**
  - ➢ **NASA is interested in collaboration with universities and private industry in developing tools**

Requirements

Performance Analysis



Input Parameters			
Kite Characteristics	Variable	Value	Units (SI)
Area	A	576	m^2
Lift Coefficient	CL	1	unitless
Lift over Drag	L/Dk	10	unitless
Load Ve[illegible]city	VL	4	m/s
Drag	Dk	100	N
Operat[illegible] Conditions			
Air Den[illegible]	rho	1.2777	kg/m^3
Wind V[illegible]city	Vw	12	m/s
Turbi[illegible]haracteristics			
Powe[illegible]duction Drag	Dp	50	N

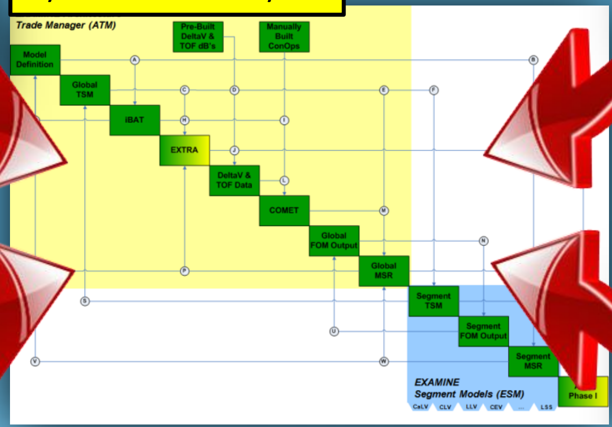
Intermediate Calculations				
Calculation	Variable	Value	Units (SI)	Equation No. from Paper:
Simple Kite				
Simple Kite Relative Lift Power	Fs	0.277546884	unitless	10
Crosswind Motion				
Crosswind Kite Relative Lift Power	Fc	14.81481481	unitless	15
Drag Power Eqns:				
Crosswind Kite Relative Drag Power	Fd	14.81481481	unitless	20
Wind Power Density Calculation				
Wind Power Density	Pw	1103.9328	W/m^2	2

[illegible]ver Output (using Equation 1)		
Mode	Value	Units (SI)
Simple Kite	0.176482431	MW
Crosswind Motion	9.42022656	MW
Crosswind Drag Power	9.42022656	MW

General Assumptions:
1. Weight of kite is neglected
2. Characteristics of tether, including drag are neglected
3. Power is calculated at a specific operational condition (steady state)
4. The kite is traveling at constant velocity
5. For Drag Power: Turbine losses are neglected

Note: Max. Power in Crosswind Motion (Lift Power) is Equal to the Max.
Power in the Drag Configuration (Drag Power): Fcmax = Fdmax = (4/27)*((L/Dk)^2)/2 @ VL/Vw = 1/3 for Fc and Dp/D

System-Level Analysis



Structural Analysis

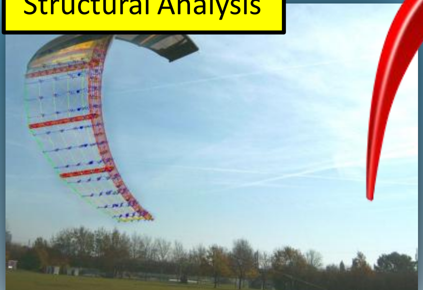
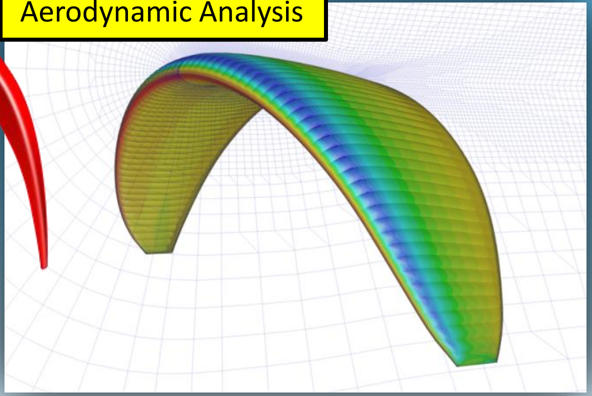


Image: Dr. J. Breukels, ASSET, TU Delft

Aerodynamic Analysis



NASA Research Capabilities for AWE

Technology Gap: Requirements Development and Figure of Merit Analysis

- **The problem cannot be solved if the requirements are not well understood**
  - **Customer requirements**
  - **Regulations**
  - **Maintainability**
  - **Environment**
  - **Life Cycle Cost (COE, ROI)**

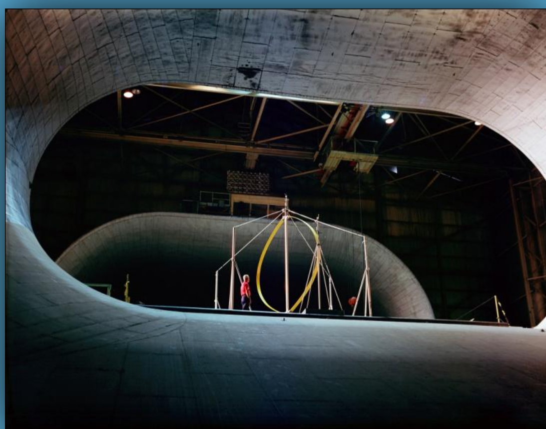
- **Requirements will vary for targeted application**
  - **Industrial wind farms supplying grid power**
  - **Niche military**
  - **Small-scale distributed power (off-grid / on-grid)**
  - **Large-scale off-grid for transportation energy**

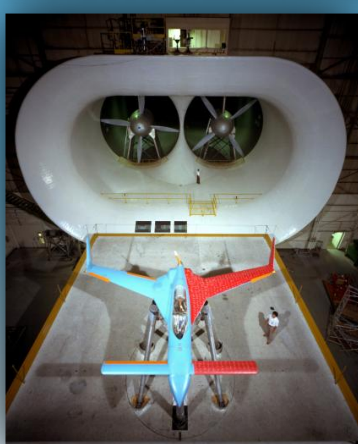
- **Rigorous Figure of Merit assessment of concepts is needed with input from <u>all</u> stakeholders**

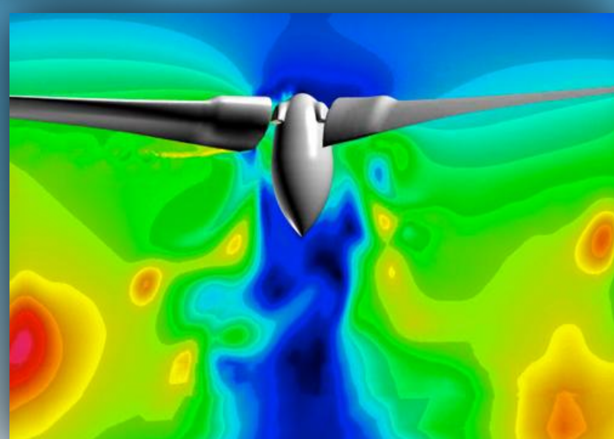
NASA Research Capabilities for AWE

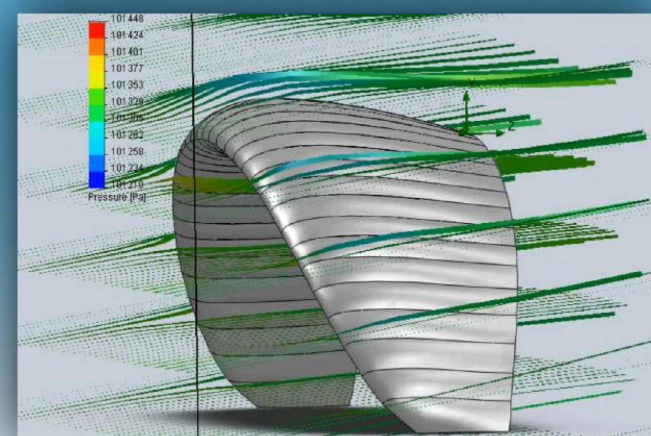
Technology Gap: Computational Fluid Dynamics tools and wind tunnel testing facilities

- **Aerodynamics – Computational Fluid Dynamics and Wind Tunnel Testing**
  - ➢ **NASA has extensive CFD and wind tunnel testing capability to apply to AWE**





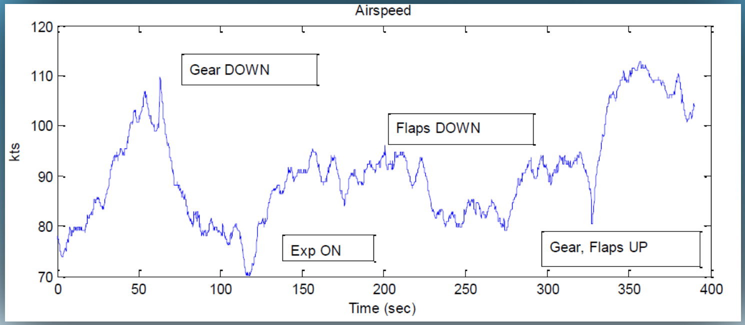


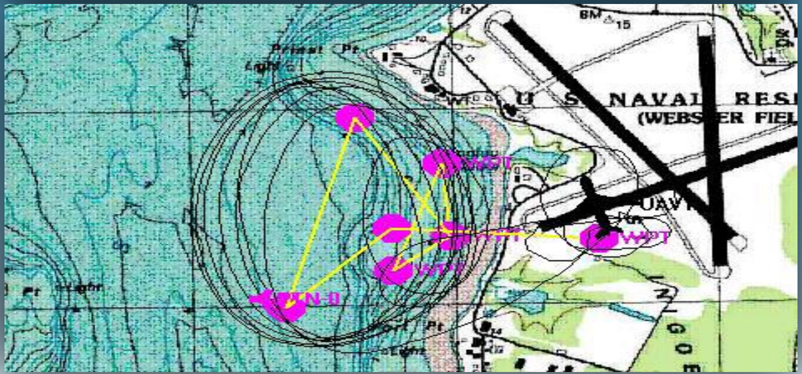


NASA Research Capabilities for AWE

Technology Gap: Autonomous controls for application to AWE

- **Controls**
  - **NASA is currently working on several autonomous UAS programs**
  - **Current flight dynamics research focusing on autonomous recovery during random wind perturbations**
  - **On-board sensor development**
  - **Navigation and control algorithm development**

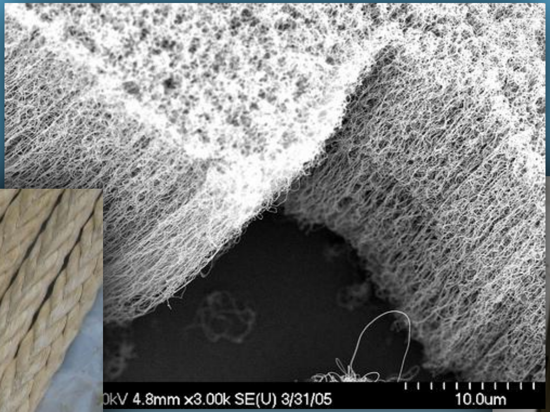




NASA Research Capabilities for AWE

Technology Gap: New materials for AWE

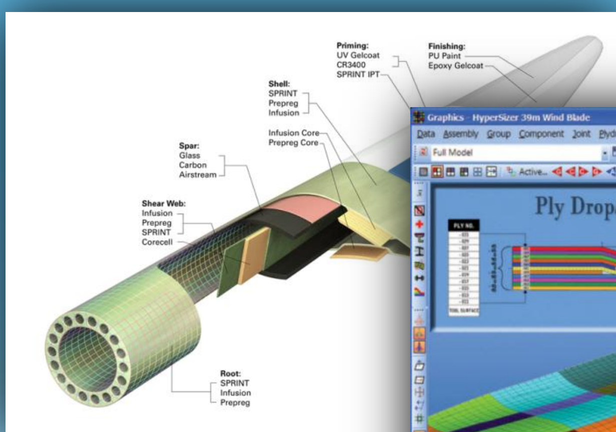
- **Materials Engineering**
  - ➢ **NASA Langley is active in nano-materials research**
  - ➢ **Durable fabrics and composites for AWE aircraft and tethers are needed to allow AWE systems to operate for long periods under extreme conditions without maintenance.**
  - ➢ **NASA has extensive facilities for materials characterization (tethers, composites, fabrics, etc.)**
  - ➢ **New materials are being developed such as Carbon NanoTubes (CNT) with multi-functional (high tensile properties + conduction) capability.**
  - ➢ **Proposal submitted to fabricate a first sub-scale CNT tether.**

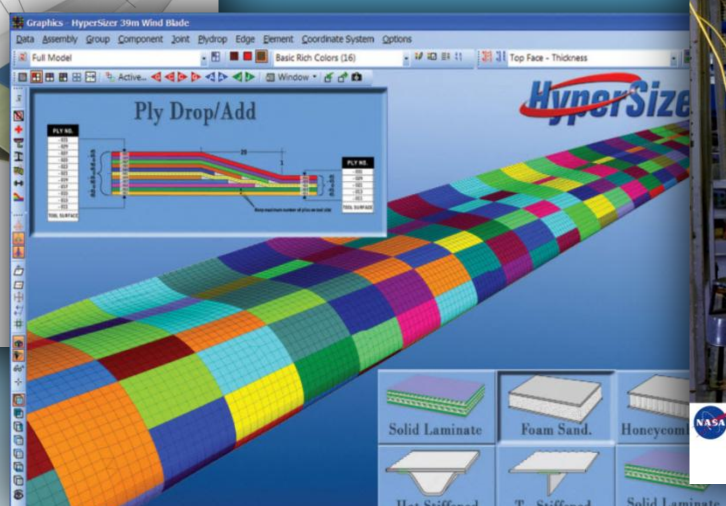


NASA Research Capabilities for AWE

Technology Gap: Structures for AWE

- **Structures**
  - ➢ **NASA has extensive composites analysis and design experience to apply to AWE technology needs**
    - **Optimization software**
    - **New applications**
    - **Structural article testing**
  - ➢ **Optimization of structures for AWE application (high g-load, durability, cost)**
  - ➢ **Certification of composites for high cycle fatigue will be an important criteria for airworthiness**

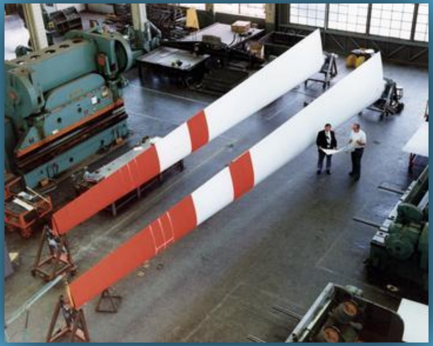


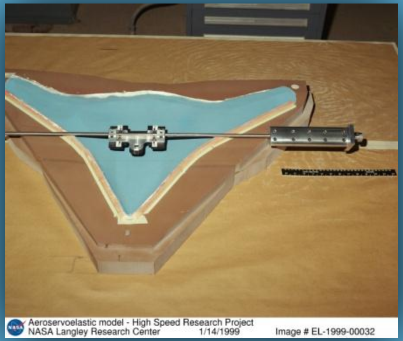


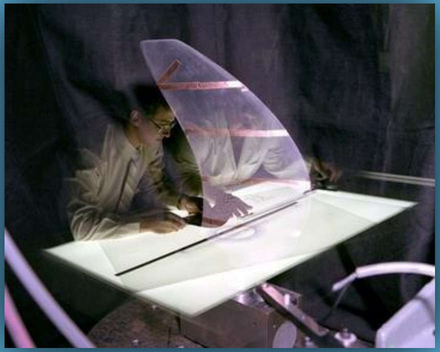
NASA Research Capabilities for AWE

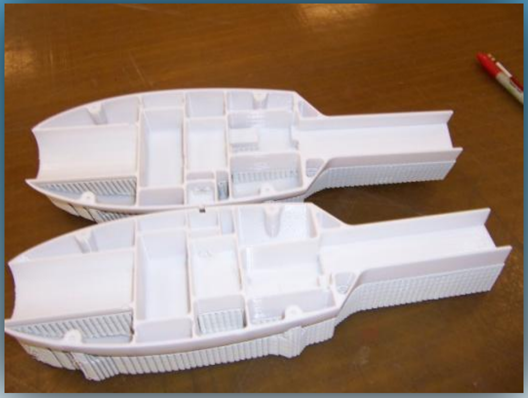
Technology Gap: Prototype fabrication

- **Experimental Prototype Fabrication**
  - ➢ Staff of 300+ technicians, model builders and prototype fabricators at NASA LaRC
  - ➢ Extensive aircraft prototype fabrication facilities
  - ➢ Specialties include composites, fabric sewing, instrumentation, rapid prototyping









Student AWE Projects

Summary

- Airspace Regulations
  - NASA is working with FAA to get clarification on the potential use of CFR 14 Part 77 for AWE.
  - International waters may be the short-term “path of least resistance”
  - NASA will work with FAA for new regulations , but this will be probably be a slow process.

- Test Sites
  - NASA is developing the capability to host AWE prototype tests at NASA facilities with restricted airspace.

- Developing NASA AWE design, analysis, and test capability
  - NASA has numerous qualified personnel and test facilities to apply to the development of AWE.
  - Collaborative efforts with private industry and academia are highly desired.