AESIR

University of Colorado at Boulder

Actuated Electromagnetic System for Ice Removal

Preliminary Design Review
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Agenda

Project Description

- Problem Statement
- Concept of Operations

Baseline Design

- Design Details
- Functional Block Diagram

Feasibility

- Critical Project Element 1: Modeling Feasibility
- Critical Project Element 2: Mechanism Design Feasibility
- Critical Project Element 3: Testing Feasibility

Project Status

- Design Recap
- Cost
- Schedule

Project Description

Project Description Baseline Design Baseline Feasibility Project Status

Background

Problem: Ice buildup on aircraft wings in flight

- Decreases Lift-to-Drag Ratio (L/D)
- Freezes control surfaces
- Reduces mission capabilities
- In extreme cases can result in a crash

Figure 1. Ice formation on wing.[1]

Currently: Several solutions exist with various limitations

  - Thermal
  - Pneumatic
  - Electro-mechanical
  - Chemical

However, solutions predominately for piloted aircraft

- Limited implementation on UAVs

Figure 2. Pneumatic de-icing on piloted aircraft.[2]

Problem Statement

Purpose of AESIR:

- De-icing solution intended for unique constraints of the Orion UAV system
    - Orion designed to fly for 5 days at 20,000 ft at 65 KIAS
    - Mission limited by icing conditions

Problem Statement: Design, build, and test a small-scale prototype of a de-icing system for the Orion UAV.

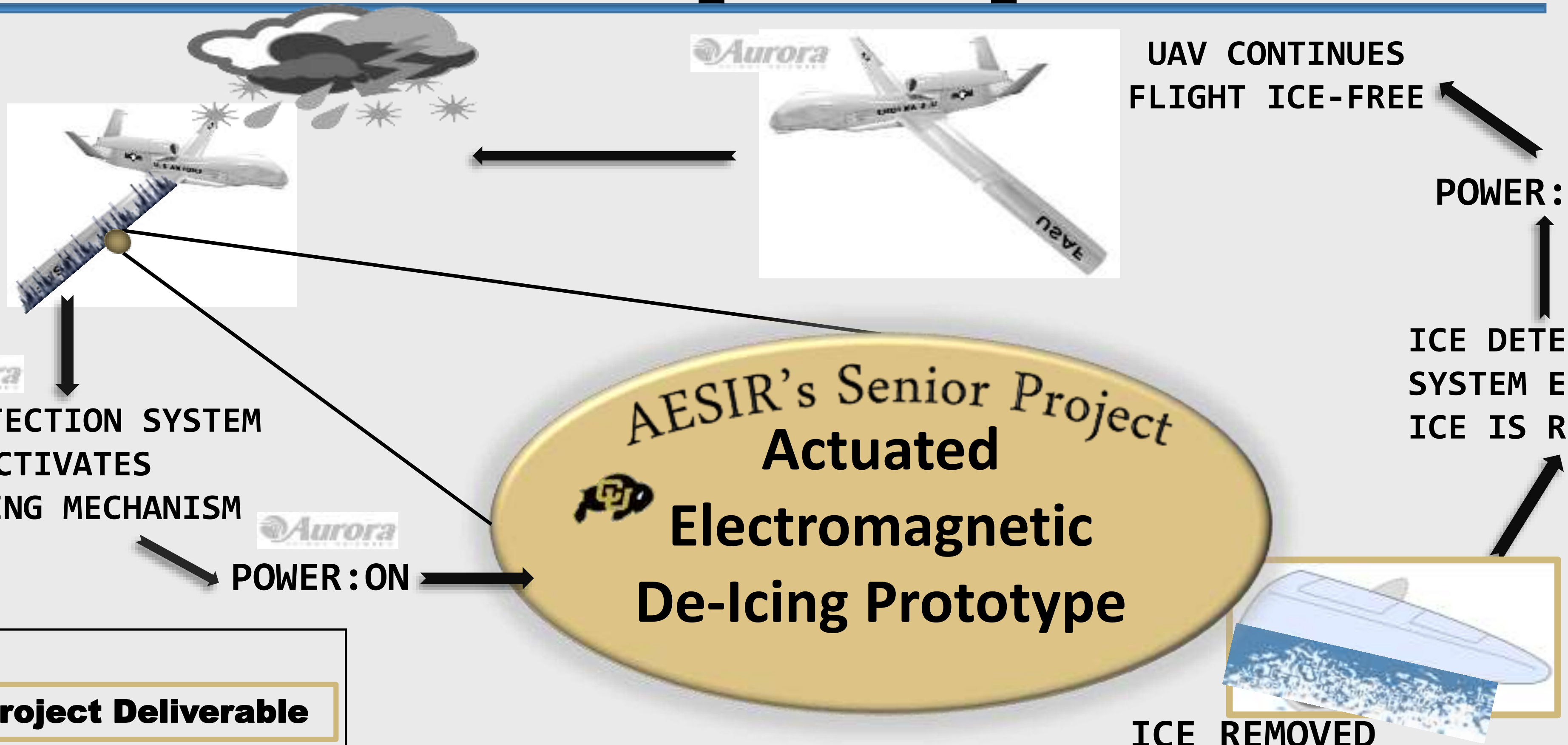
Figure 3. Orion UAV[3]

Functional Requirements

- **FR.1** The full-scale system shall be integrable with the Orion UAV.
- **FR.2** The prototype shall remove ice on wing section.
- **FR.3** The full-scale system shall use less than 4 kWh to de-ice the wing section.
- **FR.4** Integration of the de-icing mechanism with the test section shall not decrease L/D of the test section by more than 10%.

Mission Concept of Operations

SCENARIO:
UAV FLYING INTO KNOWN ICING AND ACCRETION



ICE DETECTION SYSTEM ACTIVATES DE-ICING MECHANISM

POWER:ON

AESIR's Senior Project

Actuated Electromagnetic De-Icing Prototype

ICE REMOVED FROM WING

ICE DETECTION SYSTEM ENSURES ICE IS REMOVED

POWER:OFF

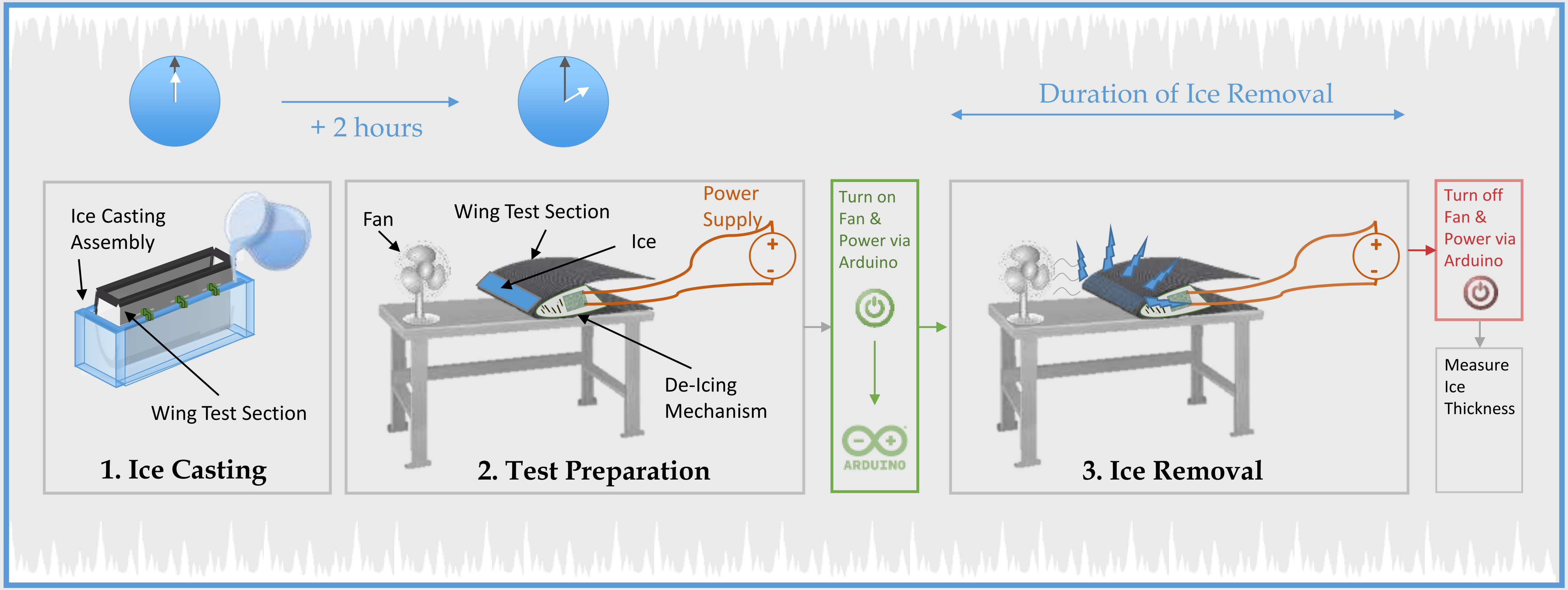
UAV CONTINUES FLIGHT ICE-FREE

LEGEND

	AESIR Project Deliverable
	AFS Hardware

Project Concept of Operations

Walk-In Freezer



+ 2 hours

Duration of Ice Removal

Ice Casting Assembly

Wing Test Section

1. Ice Casting

Fan

Wing Test Section

Ice

Power Supply

De-Icing Mechanism

2. Test Preparation

Turn on Fan & Power via Arduino

ARDUINO

3. Ice Removal

Turn off Fan & Power via Arduino

Measure Ice Thickness

Baseline Design

Selection of Baseline Design

Table 1. Design Selection Trade Study

Criteria	Weight	Electro-Magnetic	Thermo-Electric	Chemical	Pneumatic	Ultrasonic
Energy Occupancy	*35%*	7	1	10	10	6
Weight	*30%*	8	8	1	1	4
Cost	*15%*	10	10	7	4	8
Technology Readiness Level	*10%*	8	10	10	10	4
Difficulty & Complexity	*10%*	4	7	5	8	2
Total	***100%***	**7.55**	**5.95**	**6.35**	**6.2**	**5.1**

Solenoid Theory

Using electromagnets to generate large forces:

- Current in solenoid
- Solenoid generates 1st magnetic field
- 1st magnetic field creates Eddy currents in nearby metal
- Eddy currents generate 2nd magnetic field
- 1st and 2nd magnetic fields are in opposition
- Repulsive forces generated

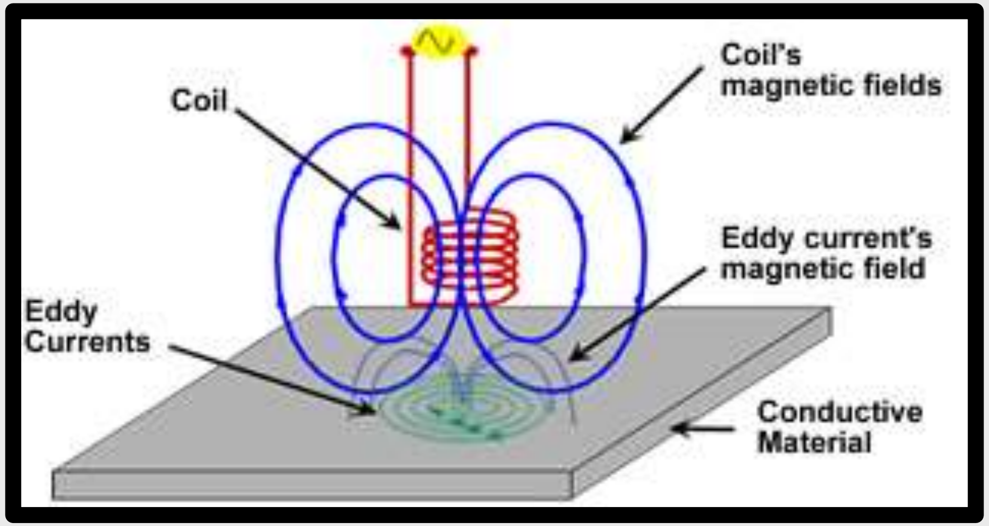


Figure 4. Solenoid theory.[4]

Test Section Design

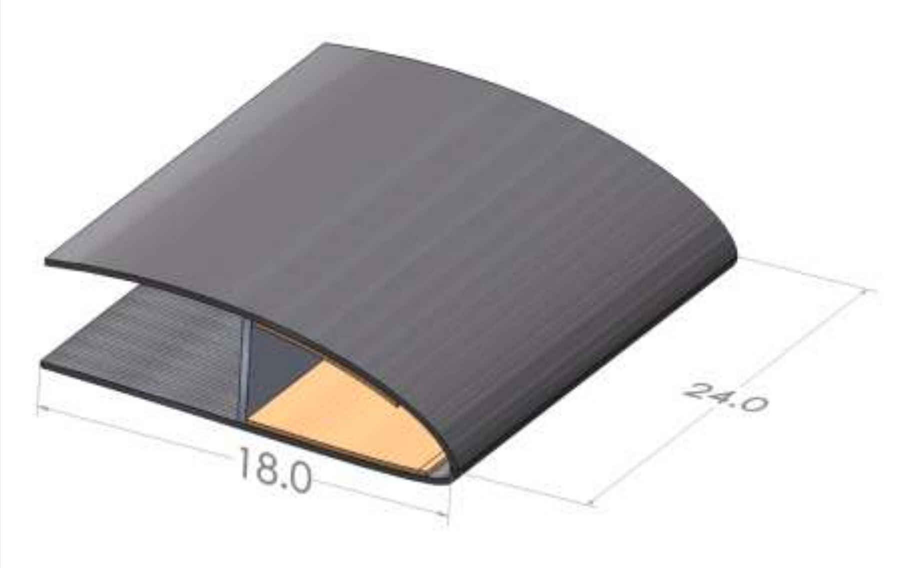
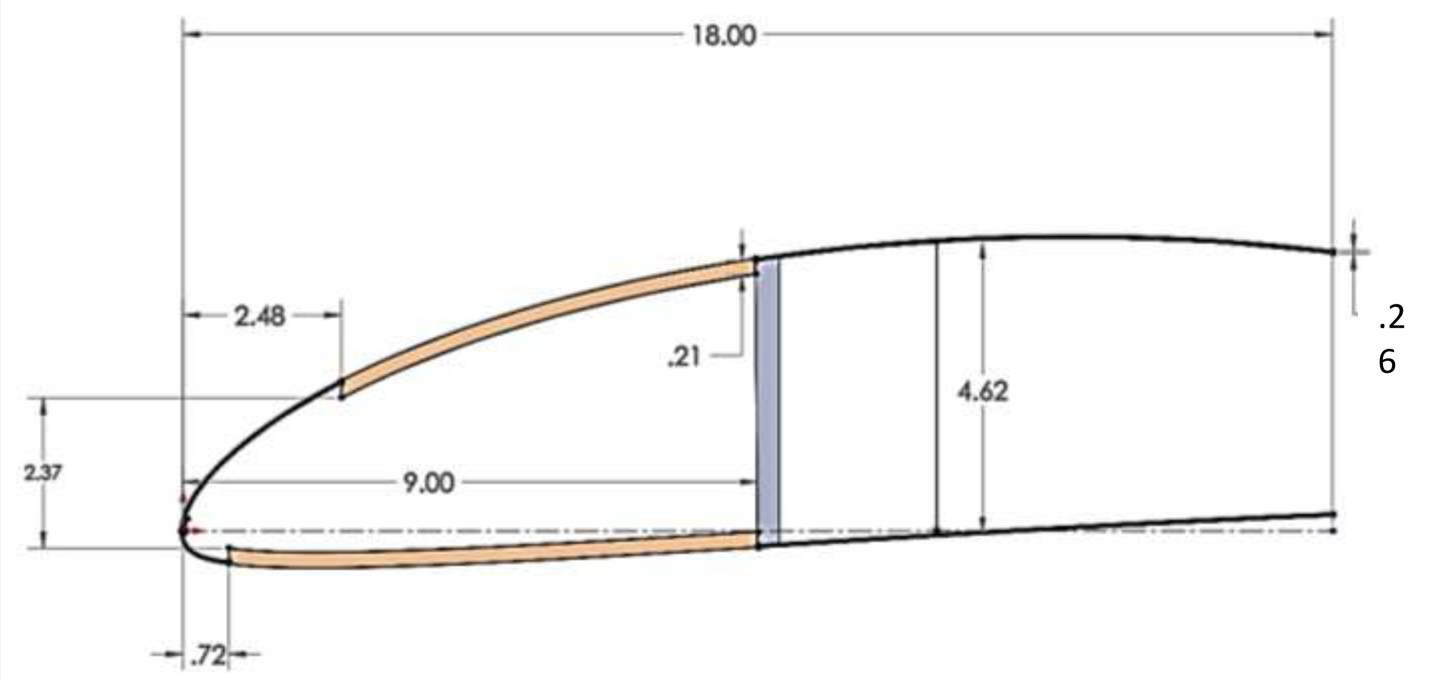


Figure 5. Test section model



.2
6

Figure 6. Side view of test section.

Integrated Design

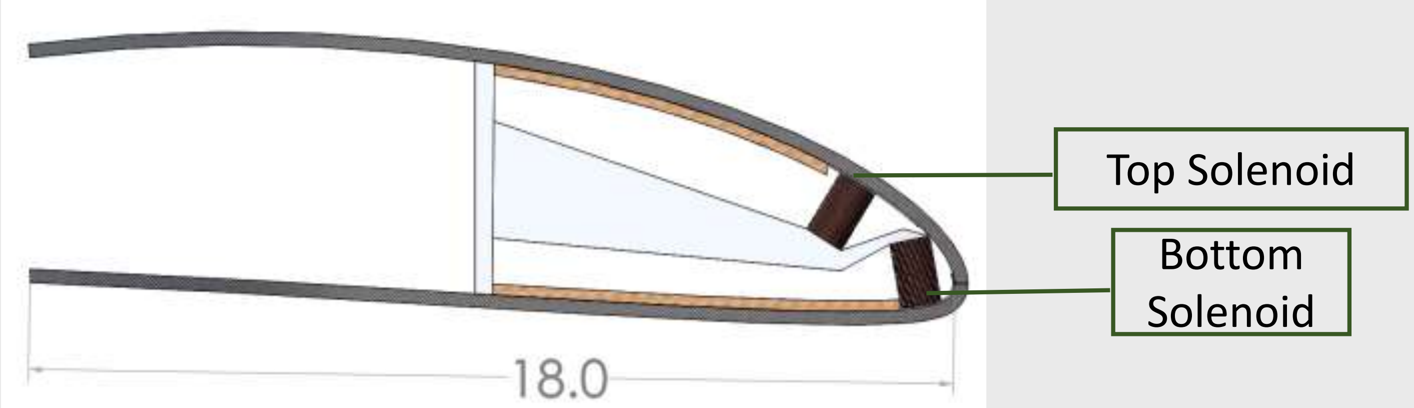


Figure 7. Side view of test section showing one set of integrated solenoids.

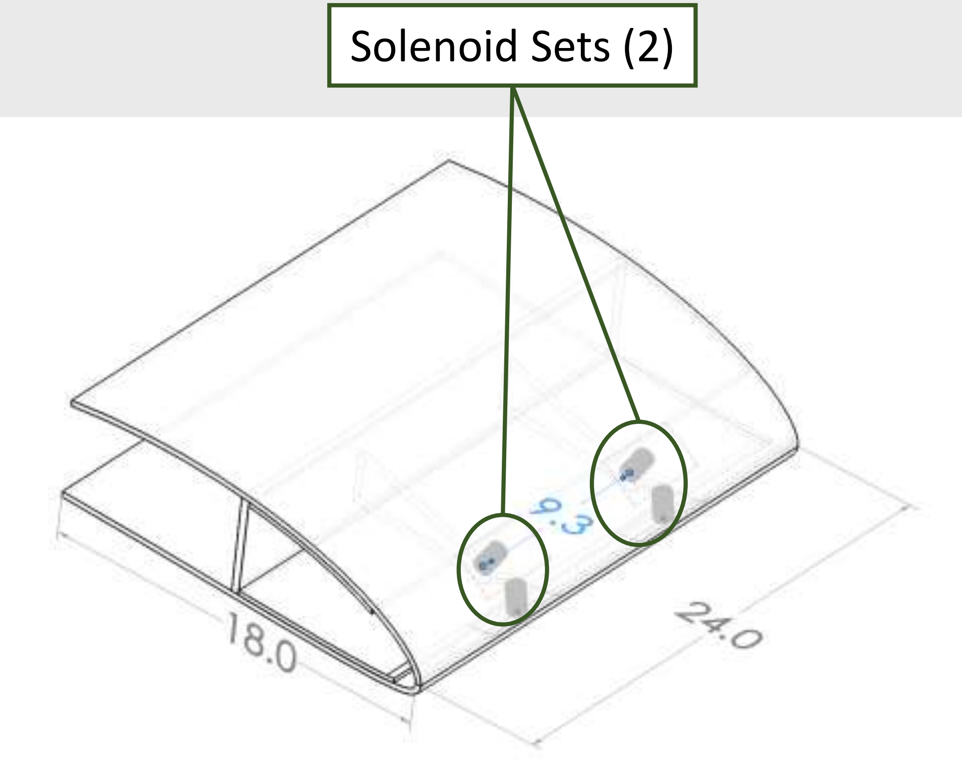
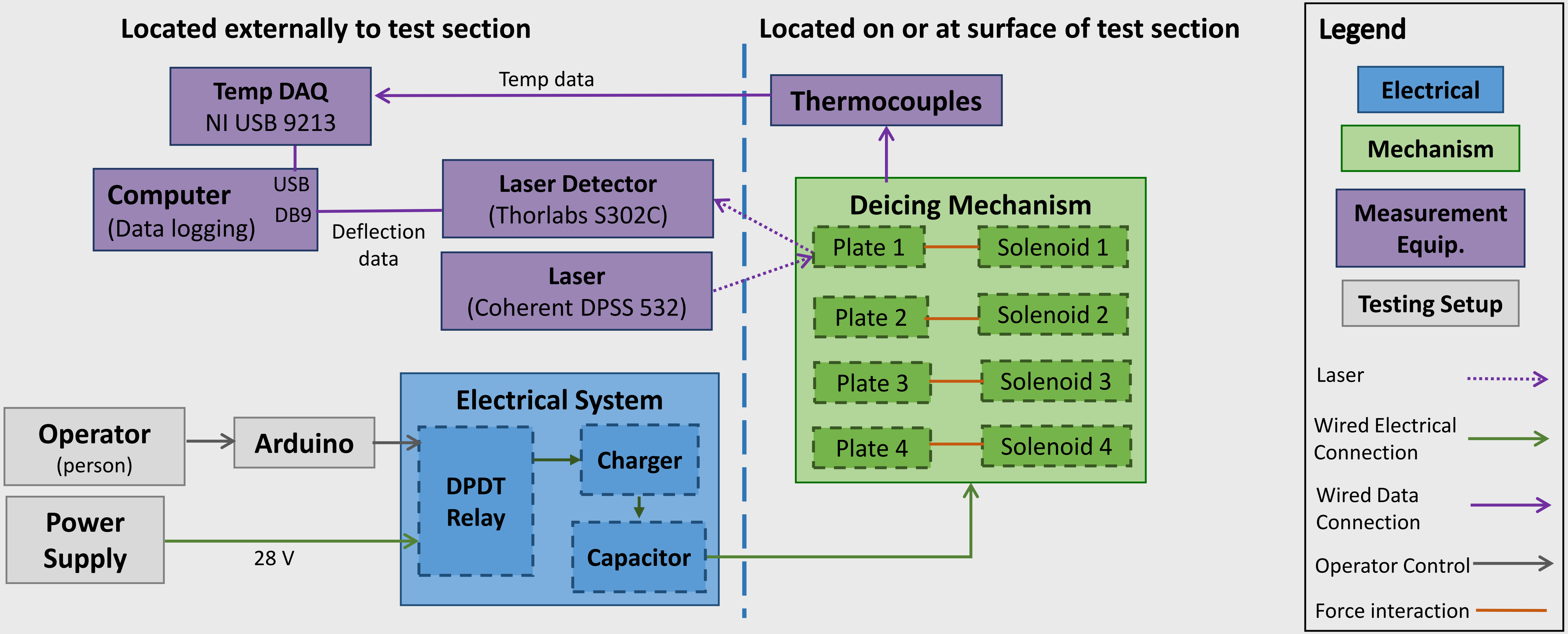


Figure 8. Test section showing both solenoid sets.

Project Description | **Baseline Design** | Baseline Feasibility | Project Status

Functional Block Diagram



Located externally to test section

Located on or at surface of test section

Temp DAQ
NI USB 9213

Temp data

Thermocouples

Computer
(Data logging)

USB

DB9

Deflection data

Laser Detector
(Thorlabs S302C)

Laser
(Coherent DPSS 532)

Deicing Mechanism

Plate 1 — Solenoid 1

Plate 2 — Solenoid 2

Plate 3 — Solenoid 3

Plate 4 — Solenoid 4

Operator
(person)

Arduino

Power Supply

28 V

Electrical System

DPDT Relay

Charger

Capacitor

Legend

Electrical

Mechanism

Measurement Equip.

Testing Setup

Laser

Wired Electrical Connection

Wired Data Connection

Operator Control

Force interaction

Design Feasibility

Critical Project Elements

CPE #1

Force and Stress Models

- Calculate force required to break ice
- Model to ensure force required does not cause structural damage

CPE #2

Mechanism Design

- Calculate solenoid parameters required
- Parameters must remain within constraints

CPE #3

Testing

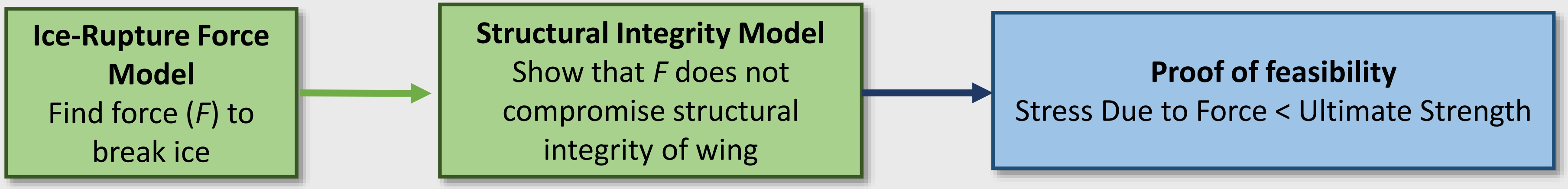
- Manufacture test section
- Cast ice
- Dynamic Testing

CPE 1: Modeling Feasibility

Relevant Requirements

FR.1 The full-scale system shall be integrable with the Orion UAV.	
DR.1.3	The installation of the system shall not damage or degrade the structural integrity of the wing.
DR.1.4	The operation of the system shall not damage or degrade the structural integrity of the wing.
FR.2 The prototype shall remove ice from wing section.	
DR.2.1	The prototype shall be capable of removing ice built-up to 0.36 in thick on test section.
SPEC.2.1.1	The ice shall cover the test section from the leading edge to 7% chord on the upper surface and 2% on the lower surface.

CPE 1: Proof of Feasibility



Ice-Rupture Force Model
Find force (*F*) to break ice

Structural Integrity Model
Show that *F* does not compromise structural integrity of wing

Proof of feasibility
Stress Due to Force < Ultimate Strength

Ice-Rupture Force Model Assumptions

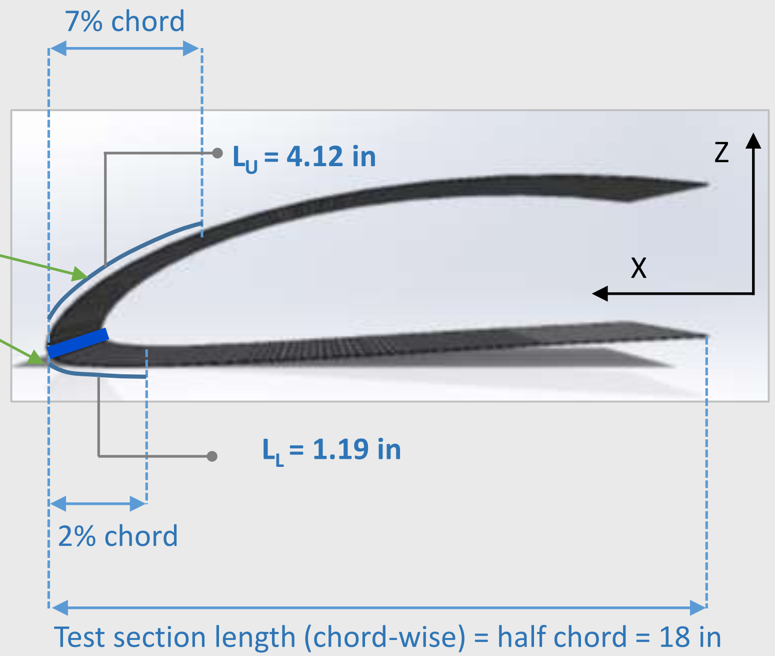
Assumptions

- Volume of ice on top & bottom surfaces = 2 independent flat plates
- Uniform thickness of ice (0.375 in)
- Chord = 36 in; Span = 24 in; Flat plate length = arc length
- Ice acts as brittle material
    - Force to crack ice = force to achieve modulus of rupture
    - Crack will propagate through thickness on formation
- Force of solenoid acts at single point

Ice-Rupture Force Determination

Structural Integrity Feasibility

Figure 9. Cross-sectional view of wing test section.



▬ = Leading Edge
▬ = Carbon Fiber

Ice-Rupture Force Model

Wing test section models for upper and lower surfaces

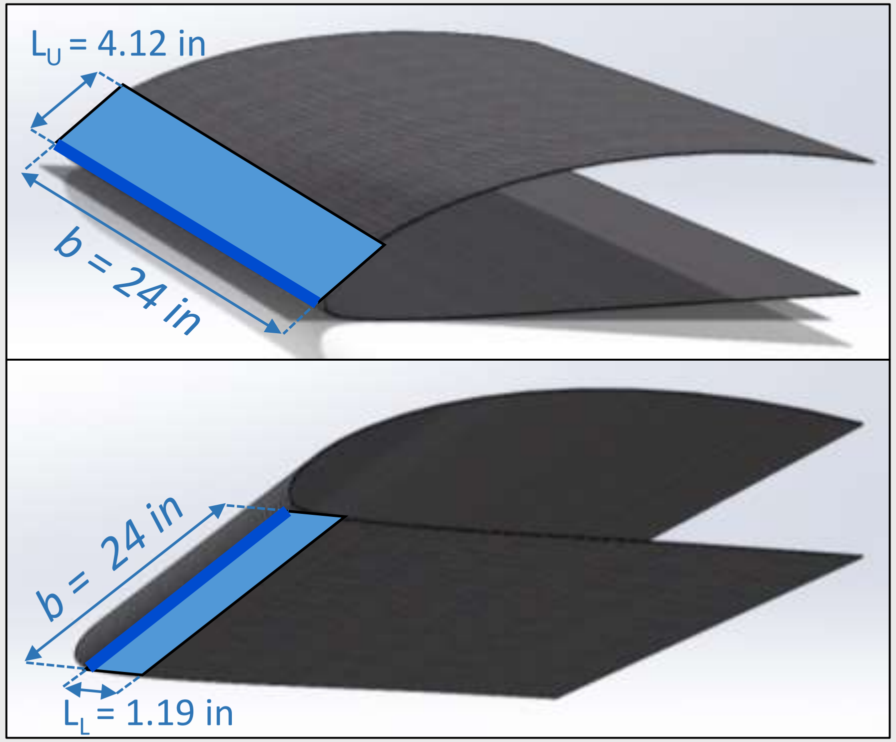


Figure 10. Wing test section models for upper and lower surfaces.

Upper Surface

Model Ice as Flat Plates

Lower Surface

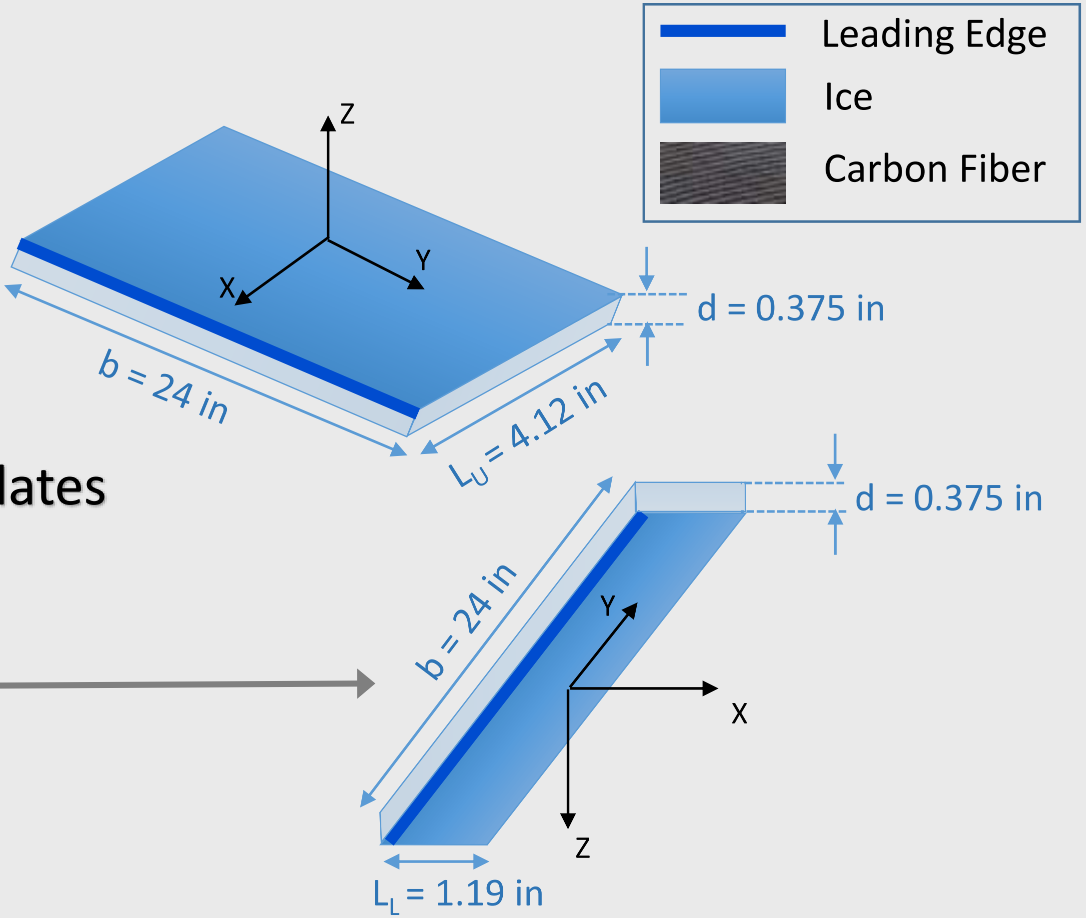


Figure 11. Model surface dimensions.

Ice-Rupture Force Model

Calculate force required to crack the ice using 3-pt loading

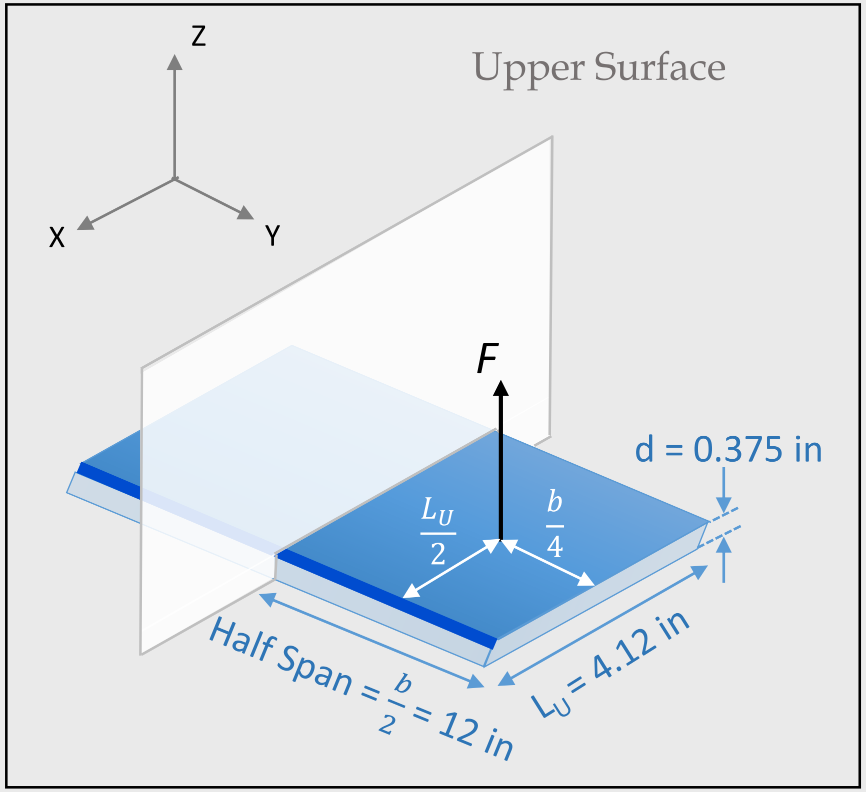


Figure 12. Upper surface dimensions.

- ▬ Leading Edge
- 🟦 Ice
- ☐ Cross-sectional cut

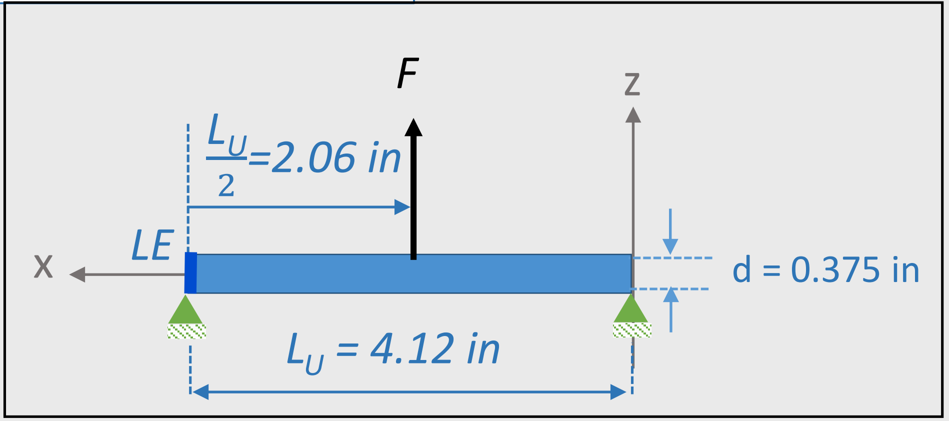


Figure 13. Upper surface as a beam.

Modulus of rupture of ice[5]: $\sigma = 246.56\ psi$

$$\sigma = \frac{3FL}{2bd^2}\ ^{6} \longrightarrow F = \frac{\sigma 2bd^2}{3L}$$

$$\boxed{F_U = 67.31\ lb} \qquad \boxed{F_L = 234.06\ lb}$$

Structural Integrity Model

Force required to break ice must not damage structure of wing surface

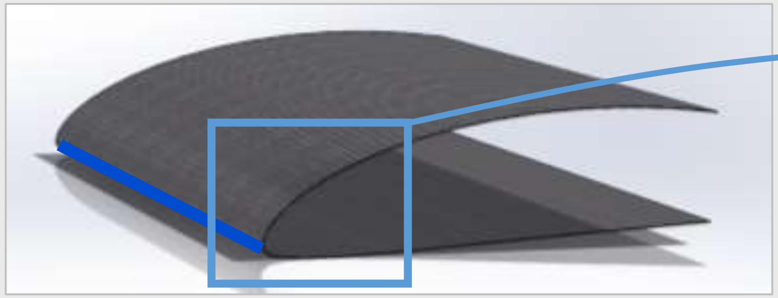


Figure 14. Carbon fiber wing test section.

Model force on wing using beam analysis with boundary conditions

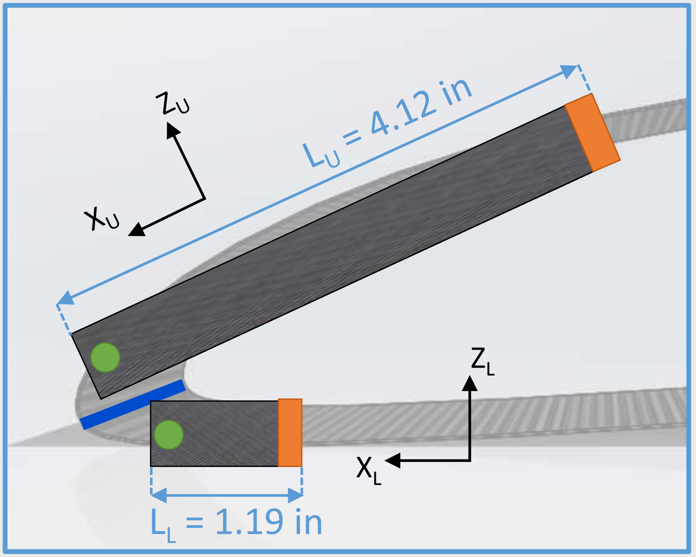


Figure 15. Carbon fiber wing test section with beams.

● Simple Support
▮ Fixed Support

Further Assumptions for Beam Analysis

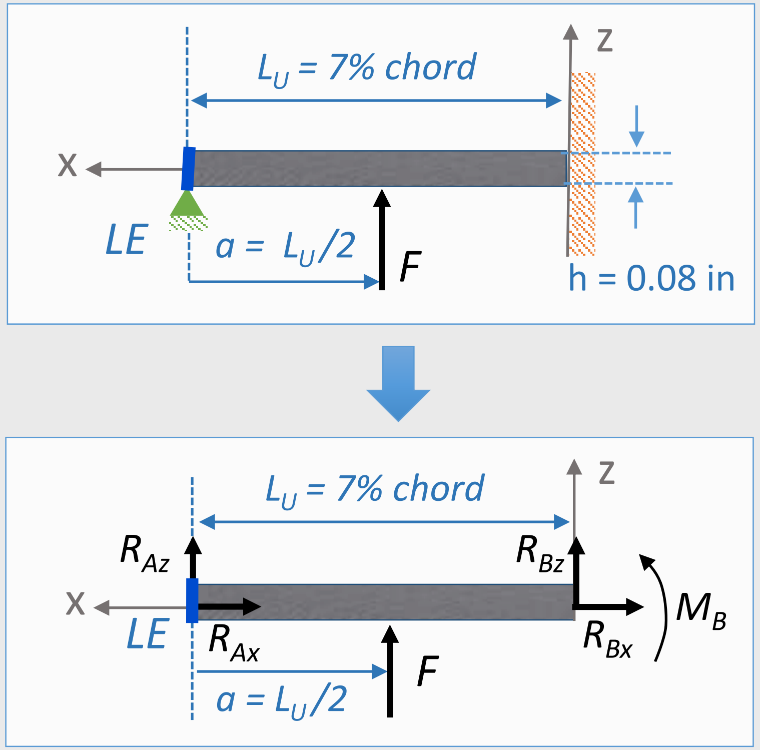
- Straight carbon fiber beam
- Leading edge → simple support
- Boundary → fixed support
- Force acts perpendicular at single point in center of 2D beam
- Material uniform thickness (both upper and lower beam models) = 0.08 in

━ Leading Edge
▬ Carbon Fiber

Structural Integrity Model (cont.)

Analyze internal forces to prove feasible

Upper Surface FBD for Carbon Fiber Beam Analysis



Equations for given Boundary Conditions

Safety Factor = 1.7

$\sigma_{allowable} = \sigma_i / FOS$

Shear Stress	$\tau = \frac{F - R_{Az}}{A} = \frac{F - R_{Az}}{{}^{b}/_{2} \cdot h}$
Bending Moment	$M_{b,max} = -0.1924FL$
Max Stress from Bending	$\sigma_{max} = \frac{({}^{h}/_{2}) \cdot M_{b,max}}{I}$
Impulse Stress	$\sigma_i = 2\sigma_{max}$

Property	Calculated Stress [ksi]	Relation	Max Allowable Stress [ksi]	Feasible?
τ_U	0.286	<	7.68	YES
τ_L	0.286	<	7.68	YES
σ_U	17.0	<	51.2	YES
σ_L	4.91	<	51.2	YES

CPE 1: Modeling Feasibility Conclusions

CPE 1 – Model the force required to break ice off wing test-section surface

Findings from Feasibility Analysis

- Max required force to crack ice = **234.06 lb**
- With safety factor and impulse model…
  - $\sigma_{U,max,calc} = 33\%\ \sigma_{allowable}$
  - $\sigma_{L,max,calc} = 9.6\%\ \sigma_{allowable}$
  - $\tau_{max,calc} = 3.7\%\ \tau_{allowable}$

Future Work

- ANSYS model of structural integrity
  - 2-D/3-D
- Verify model with testing data
  - Measure distance to which ice cracks
  - Verify some model assumptions
  - Revise if necessary the number and strength of solenoid actuators

CPE 2: Mechanism Design Feasibility

Relevant Requirements

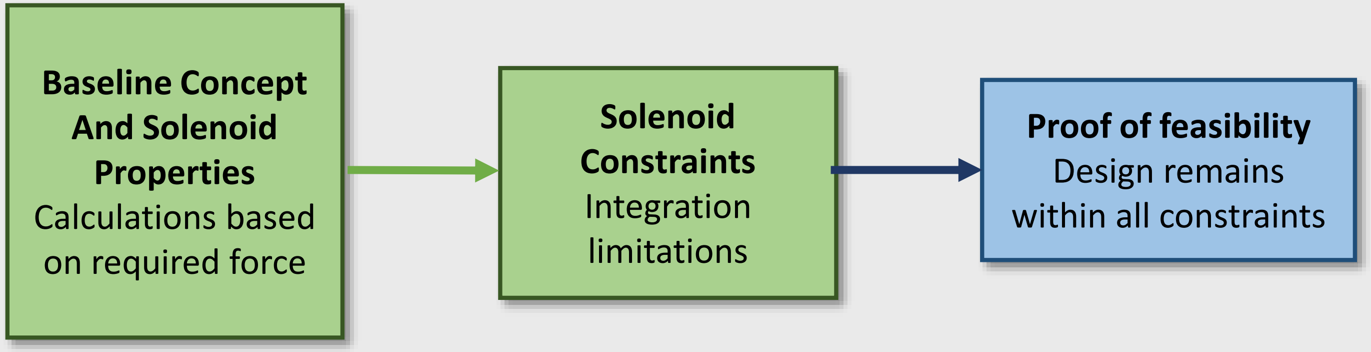
FR.1 The full-scale system shall be integrable with the Orion UAV.	
DR.1.1	The full-scale system shall weigh less than 100 lb.
DR.1.2	The de-icing mechanism shall be integrable with a DAE11 airfoil.
DR.1.2.1	The test section chord shall be 36 in.
DR.1.2.2	The internal components of the de-icing mechanism shall fit between the leading edge and half chord
FR.2 The prototype shall remove ice on wing section.	
DR.2.1	The prototype shall be capable of removing ice built-up to 0.36 in thick on test section.
SPEC.2.1.1	The ice shall cover the test section from the leading edge to 7% chord on the upper surface and 2% on the lower surface.

CPE 2: Mechanism Design Feasibility

Relevant Requirements

FR.3 The full-scale system shall use less than 4kW-hr to de-ice the wing section.	
DR.3.2	The full-scale system instantaneous power draw shall be at most 2 kW.

CPE 1: Proof of Feasibility



Baseline Concept And Solenoid Properties
Calculations based on required force

Solenoid Constraints
Integration limitations

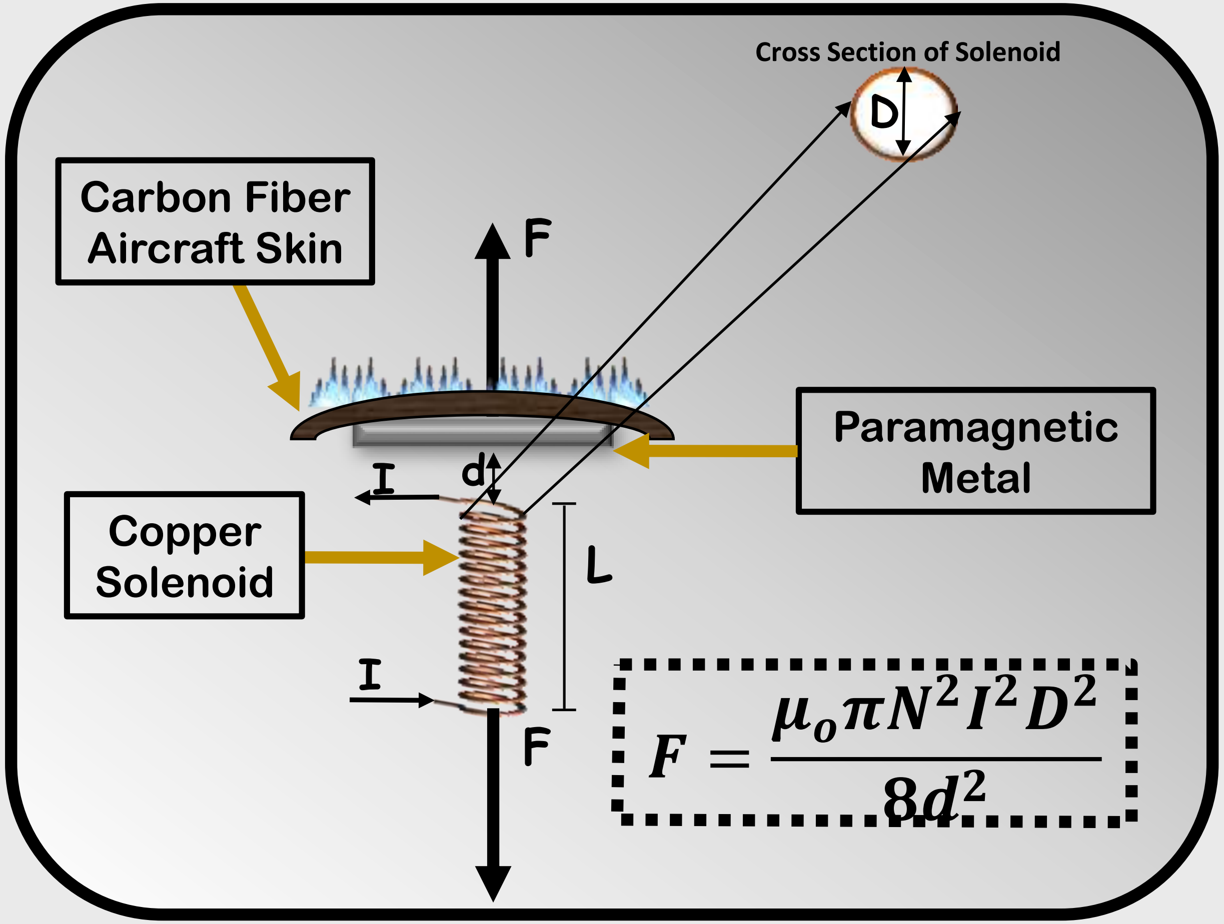
Proof of feasibility
Design remains within all constraints

Baseline Concept

- Basic copper coil solenoid
- Force dependent on various parameters

To <u>increase</u> force:

- Large current (I)
- Many coil turns (N)
- Large diameter (D)
- Small gap distance (d)



$$F = \frac{\mu_o \pi N^2 I^2 D^2}{8d^2}$$

Solenoid Properties Calculations

Subject: Bottom solenoid must generate **$F = 231.4\ lb_f$**

- Bottom requires more F than top, analysis to see if larger F is achievable

Assumptions:

  - D = 2.5 in | d = 0.02 in | t = 12 AWG copper wire
  - No energy loss due to heat & structural absorption
  - Negligible magnetic field interaction between solenoids
  - Instantaneous current draw

Dependent Variables:

  - N- # of turns
  - I- Current draw from power source

$$\boxed{F = \frac{\mu_o \pi N^2 I^2 D^2}{8d^2}}$$ 12

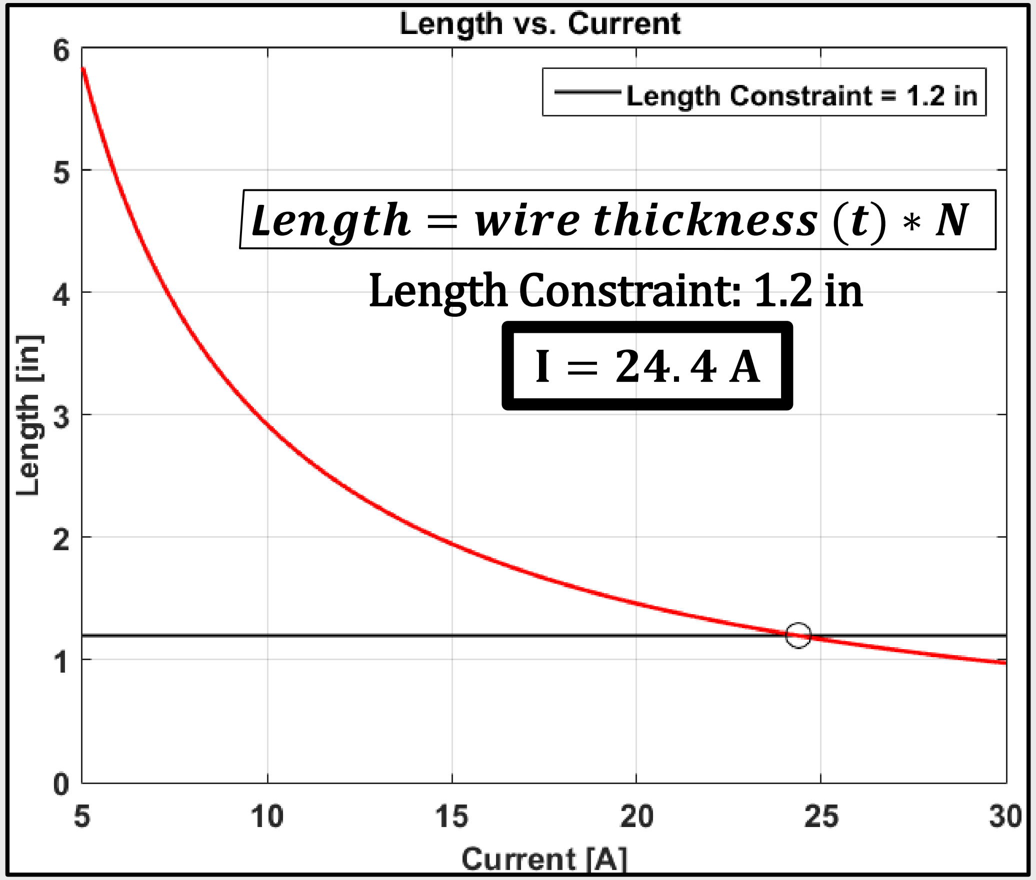


Figure 18. Length vs Current of solenoid.

Solenoid Properties Calculations

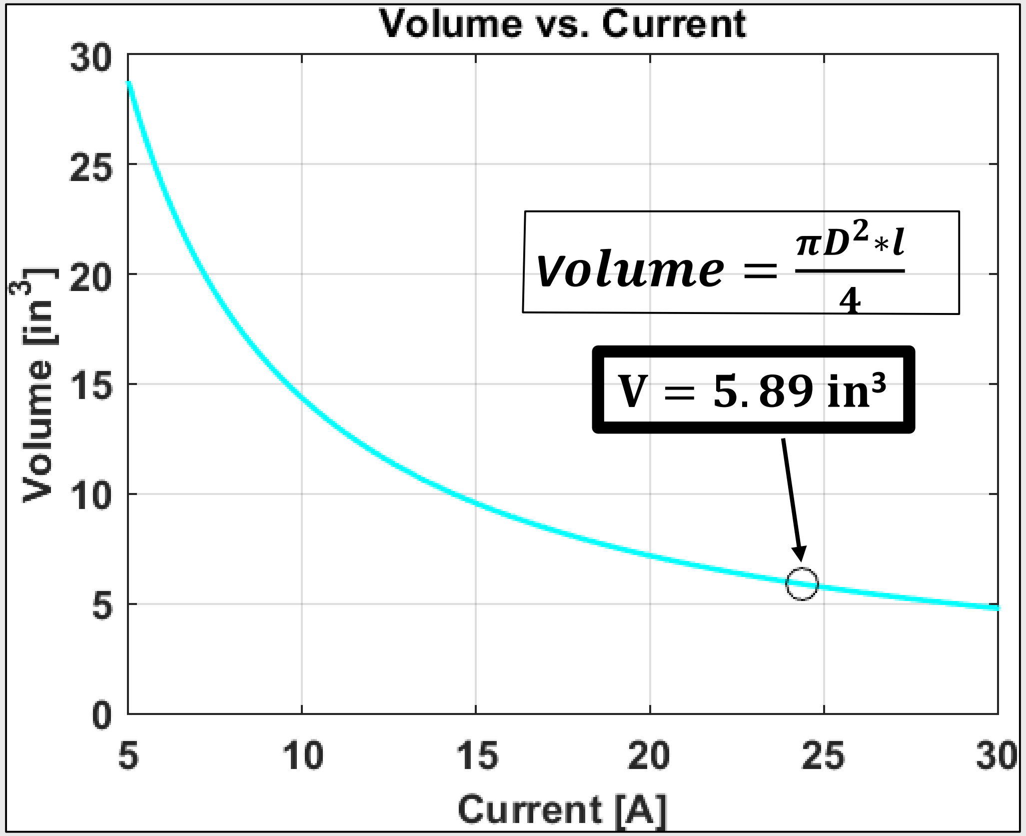


Figure 19. Volume vs Current of solenoid.

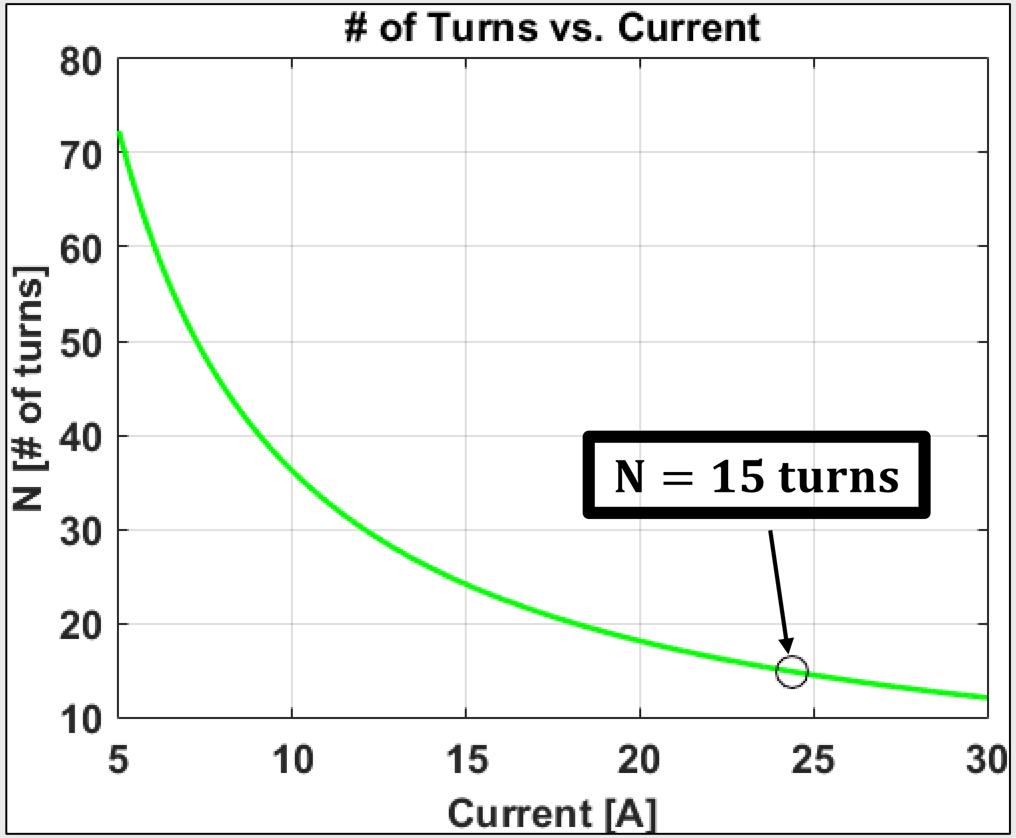


Figure 20. # of Turns vs Current of solenoid.

Solenoid Properties Summary

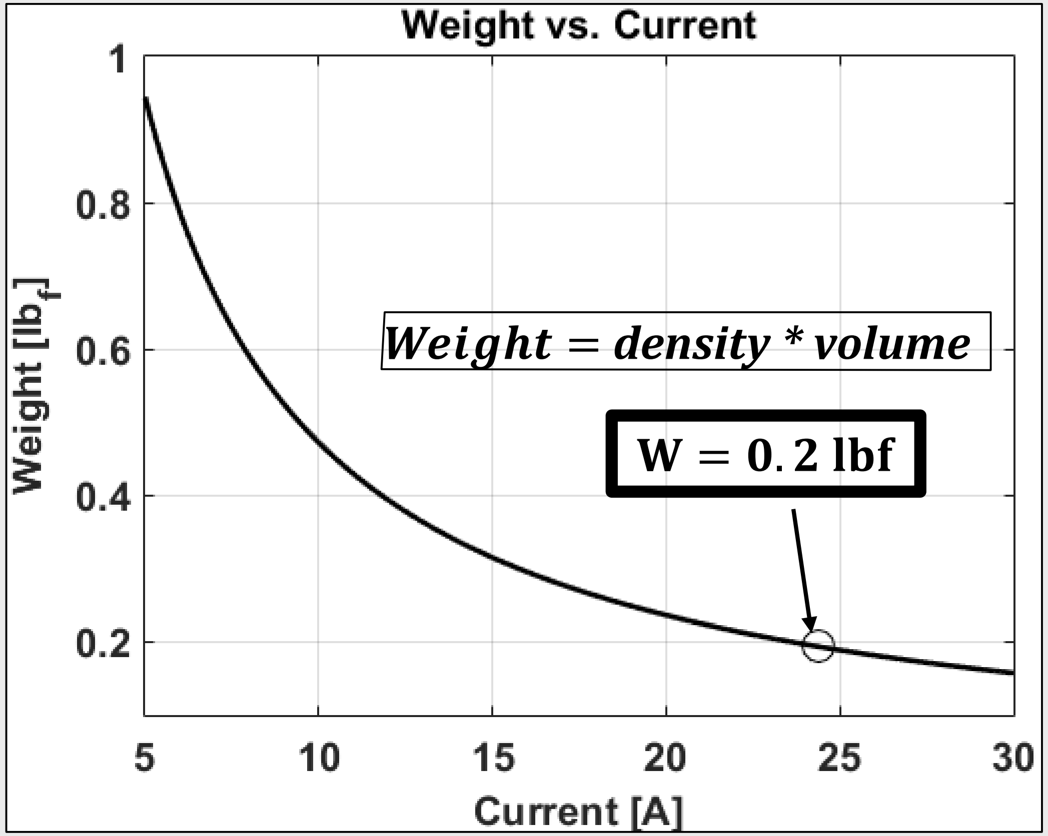


Figure 21. Weight vs Current of solenoid.

Solenoid Requirements to generate *$F = 234.06\ lb_f$* :

Property	Value
Diameter – D	2.5 in
Distance – d	0.02 in
Thickness of wire – t	12 AWG (0.0808 in)
Length – L	1.2 in
Instantaneous Current – I	24.4 A
Volume – V	5.89 in^3
# of turns – N	15
Weight - W	0.2 lb_f

Project Description | Baseline Design | **Baseline Feasibility** | Project Status

Solenoid Integration Feasibility

Basic solenoid design can achieve force required but does not fit volume constraints

- Limited by safe current, wire gauge, and leading edge integration constraints

Note: Calculations done for bottom solenoid since bottom surface requires greater force and has more stringent integration constraints

Property	Basic Solenoid	Size Limitations
Diameter – D	2.5 in	Bottom Solenoid: 0.75 in
Length – L	1.2 in	Bottom Solenoid: 1.25 in

To make feasible, considering different solenoid designs:

1. Magnetic core solenoid design
2. Rectangular solenoid
3. Test section change

Solenoid Integration Feasibility

1. Magnetic core solenoid design
    - Adding magnetic core to basic solenoid increases strength of magnetic field, increases F produced
        - Decrease size and/or change shape of solenoid
    - Different core shapes: E-core transformer

Figure 22. E-core.[13]

2. Rectangular Solenoid
    - Change shape of solenoid to better fit integration constraints
    - Ribbon wire solenoid

Figure 23. Ribbon wire solenoid. [14]

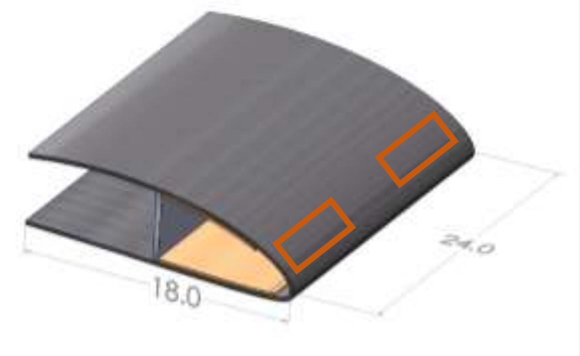


Figure 24. Rectangular solenoid diagram on test section.

Solenoid Integration Feasibility

3. Test Section change
   - Test section scale selected as half
     - Test section chord = 3 ft
     - Orion chord = 6 ft
   - Increase test section chord to ease integration constraints
   - Solenoids do not scale linearly so test section represents more stringent integration constraints than a large scale system would have

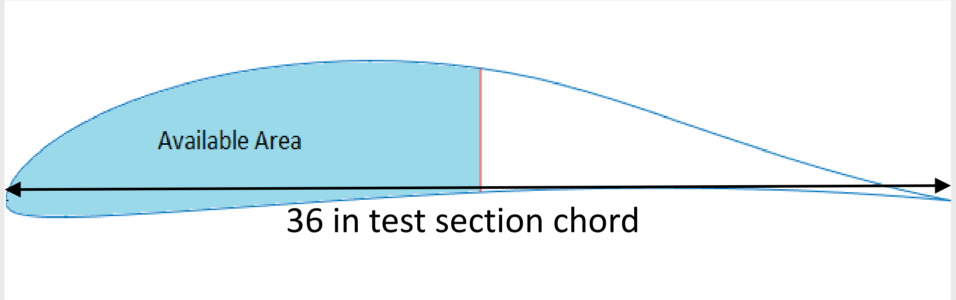


Figure 25. Test section limitations.

CPE 2: Mechanism Design Feasibility Conclusions

CPE 2 – Design the mechanism to achieve required force and fit integration and power constraints

Findings from Feasibility Analysis

- For preliminary modeling, only calculated basic solenoid
  - Force required is feasible but will have to adjust design
  - Calculations begun for rectangular solenoid
- Alternate solenoid designs available to achieve force and integration
- Preliminary calculations show power and mass to be within limits

Future Work

- Complete calculations for potential solenoid designs
- Select design based on integration constraints

CPE 3: Testing Feasibility

Relevant Requirements

FR.1 The full-scale system shall be integrable with the Orion UAV.	
DR.1.2	The de-icing mechanism shall be integrable with a DAE11 airfoil.
DR.1.2.1	The test section chord shall be 36 in.
FR.2 The prototype shall remove ice on wing section.	
DR.2.1	The prototype shall be capable of removing ice built-up to 0.36 in thick on test section.
SPEC.2.1.1	The ice shall cover the test section from the leading edge to 7% chord on the upper surface and 2% on the lower surface.
SPEC.2.1.2	The prototype shall remove ice in an environment with wind speed ≥ 12 knots indicated.

CPE 1: Proof of Feasibility

Test Section Manufacturing
Test section manufacturing plan

→

Ice Casting Procedure
Ability to consistently attach ice to the test section

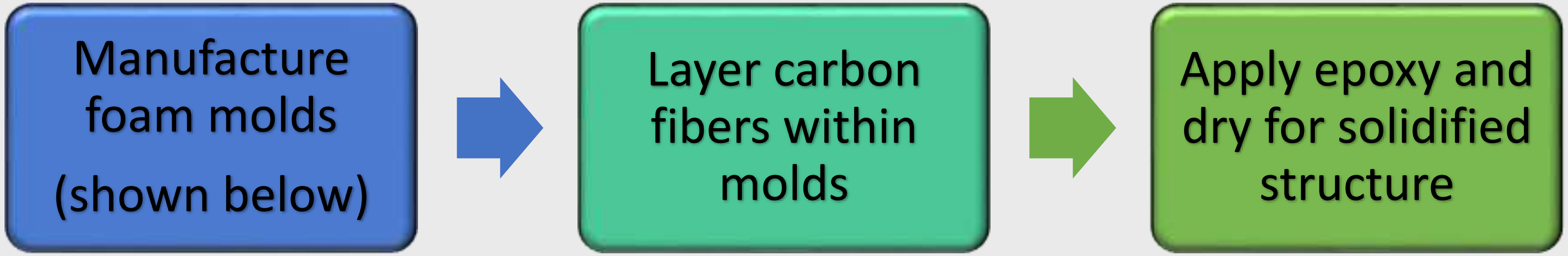
→

Testing Plan
Plan and facilities to test capabilities

→

Proof of Feasibility
All aspects of testing possible and within scope of project

Test Section Manufacturing Molds



Manufacture foam molds

(shown below)

Layer carbon fibers within molds

Apply epoxy and dry for solidified structure

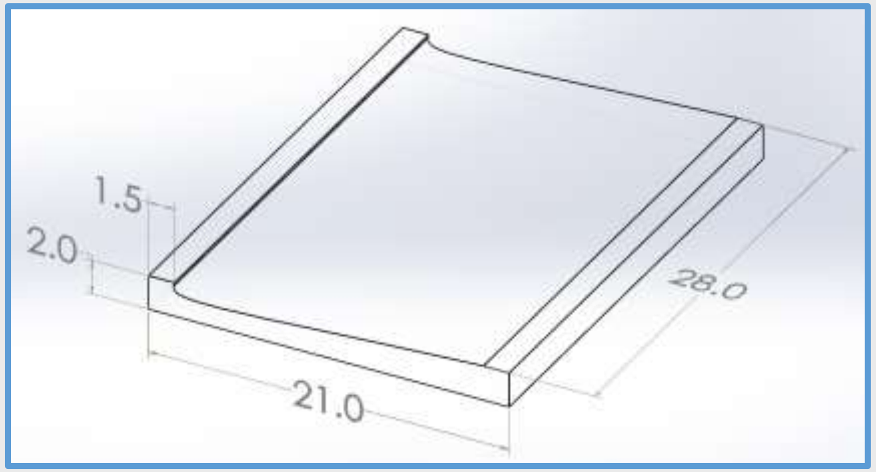


Figure 26. Lower surface mold.

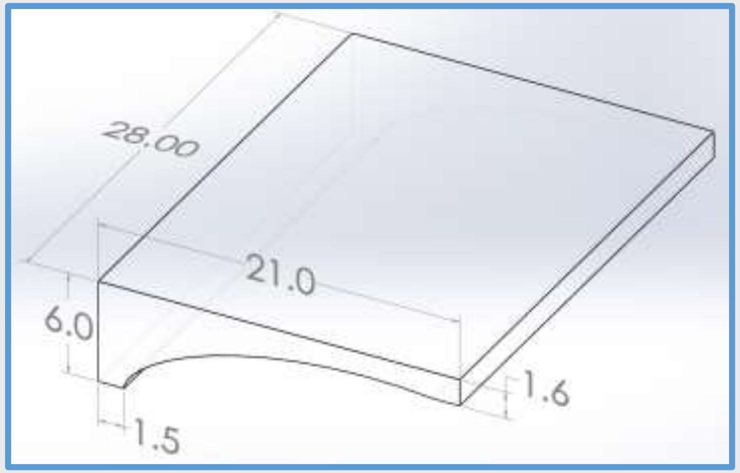


Figure 27. Upper surface mold.

Note – all dimensions are in inches

Test Section Manufacturing Interior Plates

Several options for manufacturing target metal plates:

- Manufacturing plate as one continuous piece

- Connecting smaller, flat pieces with aluminum tape (aluminum optional, must be a conductive adhesive)

- Replacing the plates with layers of aluminum foil

Wing Test Section

Ferromagnetic metal plates

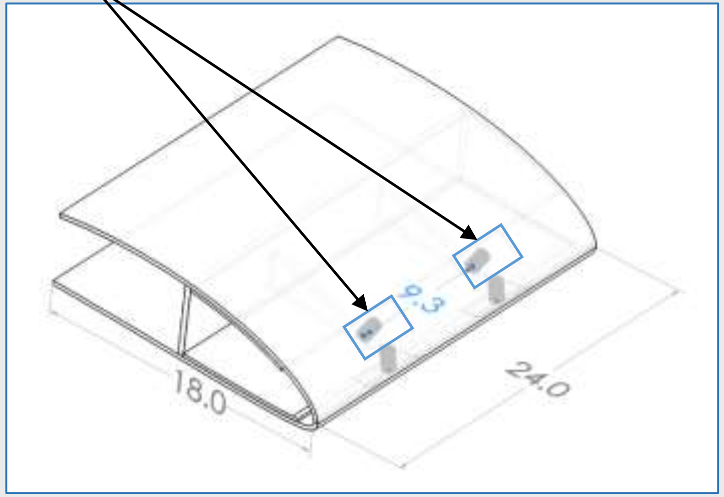


Figure 28. Interior view of ferromagnetic plates beneath leading edge

Ice Casting

Subject - Ice application on test section

- Ice thickness = 0.375 in, uniform
- Ice surface area coverage = 7% of chord on top surface and 2% chord on lower surface (measured from LE)

Method - Ice casting

- Trough structure ice mold
- Trough coated with smooth material to prevent ice adhering to mold
- End caps engraved with shape of airfoil to hold test section in place

Results

- Method used in industry
- Procedure for casting
- Design for ice mold
- Preformed small scale ice casting test

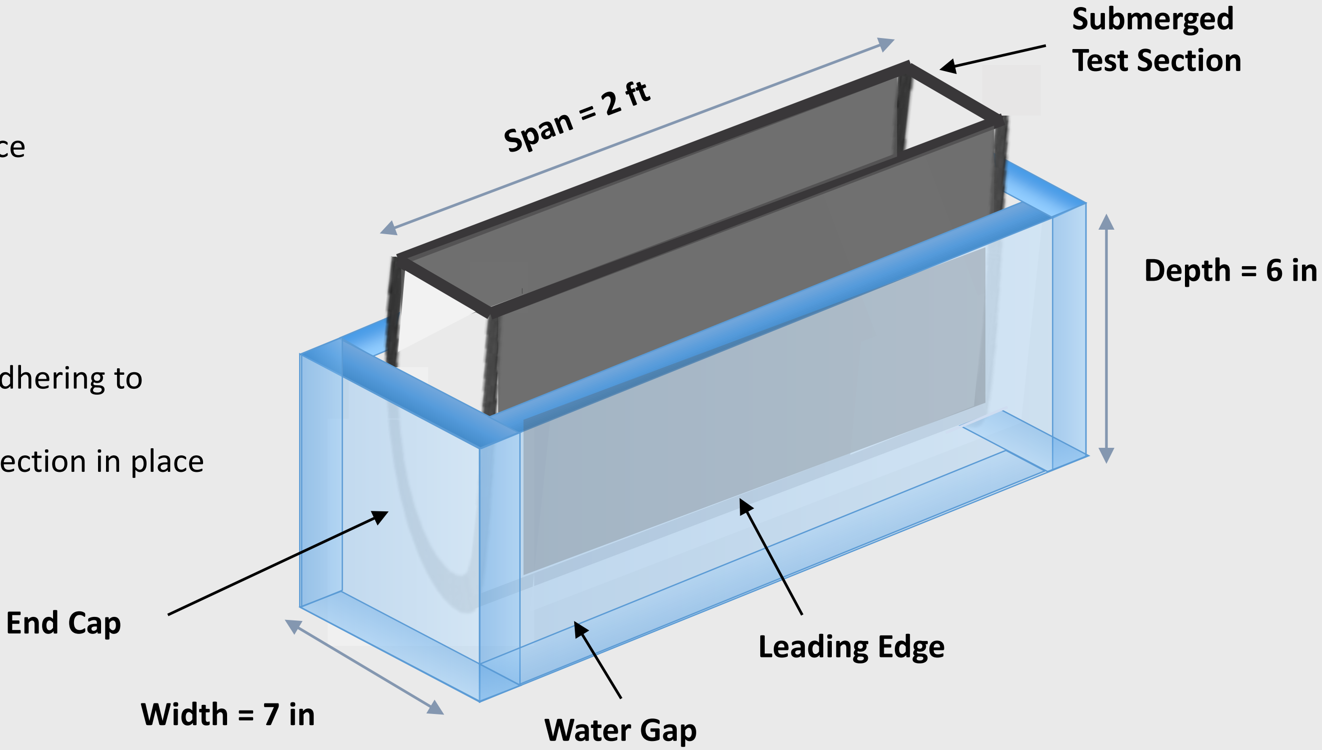


Figure 29. Ice casting assembly diagram.

Project Description | Baseline Design | **Baseline Feasibility** | Project Status

Small Scale Casting Test

- **Performed Ice casting method on carbon fiber tube:**
  - Put tube in cup of water
  - Put in freezer
  - Removed assembly from freezer
  - Ran hot water on outside of cup
  - Removed test section from cup

Figure 31. Ice cast on carbon fiber tube.

Figure 30. Ice cast on carbon fiber tube.

Testing Feasibility

Plan to test model assumptions and design functionality

Preliminary Ice Removal Test

- To occur before CDR to verify assumptions made about the designs and models
- Consists of 1 solenoid, ferromagnetic metal plate, carbon fiber
- Measure: propagation of ice cracks, displacement of carbon fiber during actuation, power draw

Later Testing

- Will include ice removal testing with wind and no wind
- Accessible resources:
  - Freezers (small and walk-in)
  - Environmental chamber
  - Large fan
  - Air Compressor
  - Leaf blower

To simulate freezing conditions

To simulate wind

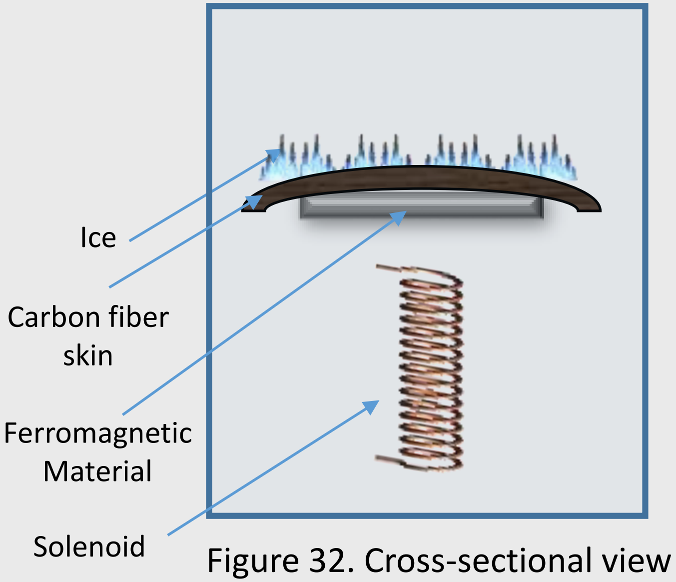


Figure 32. Cross-sectional view of solenoid and leading edge.

CPE 3: Testing Feasibility Conclusions

CPE 3 – Testing to verify design functionality and models

Findings from Feasibility Analysis

- Test section can be manufactured
- Ice casting is accomplishable

Future Work

- Preliminary Ice Removal
- Ice casting demonstration
- Test plan to verify model assumptions and prove functionality

Project Status

Recap of Design

- Force from solenoids can remove ice
- Calculated force will not damage carbon fiber skin
- Pursuing alternate solenoid designs for integration
- Test section can be manufactured
- Ice can be cast to the test section

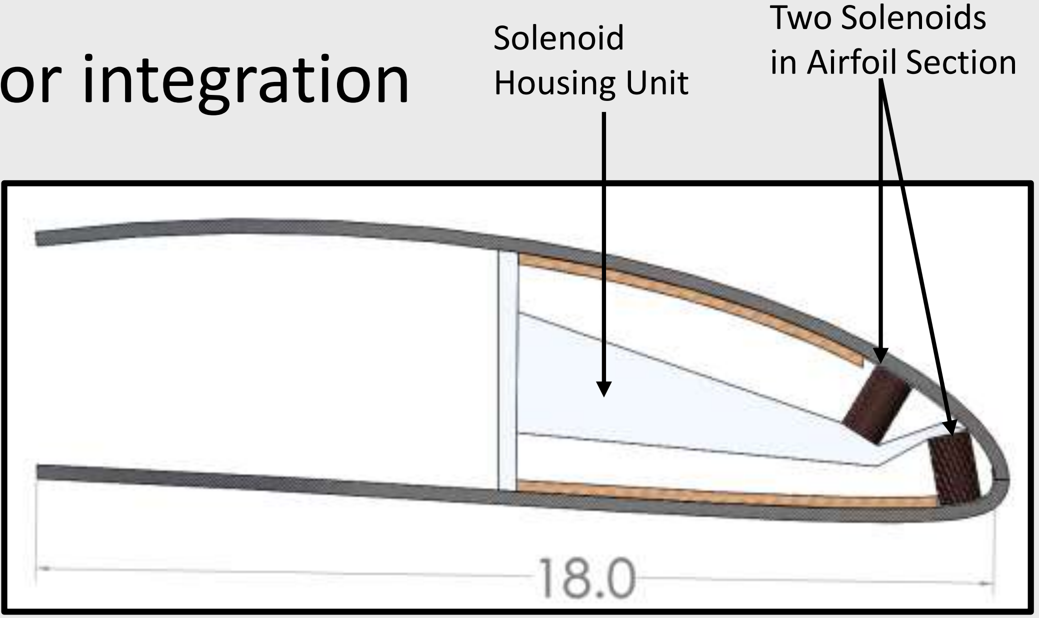
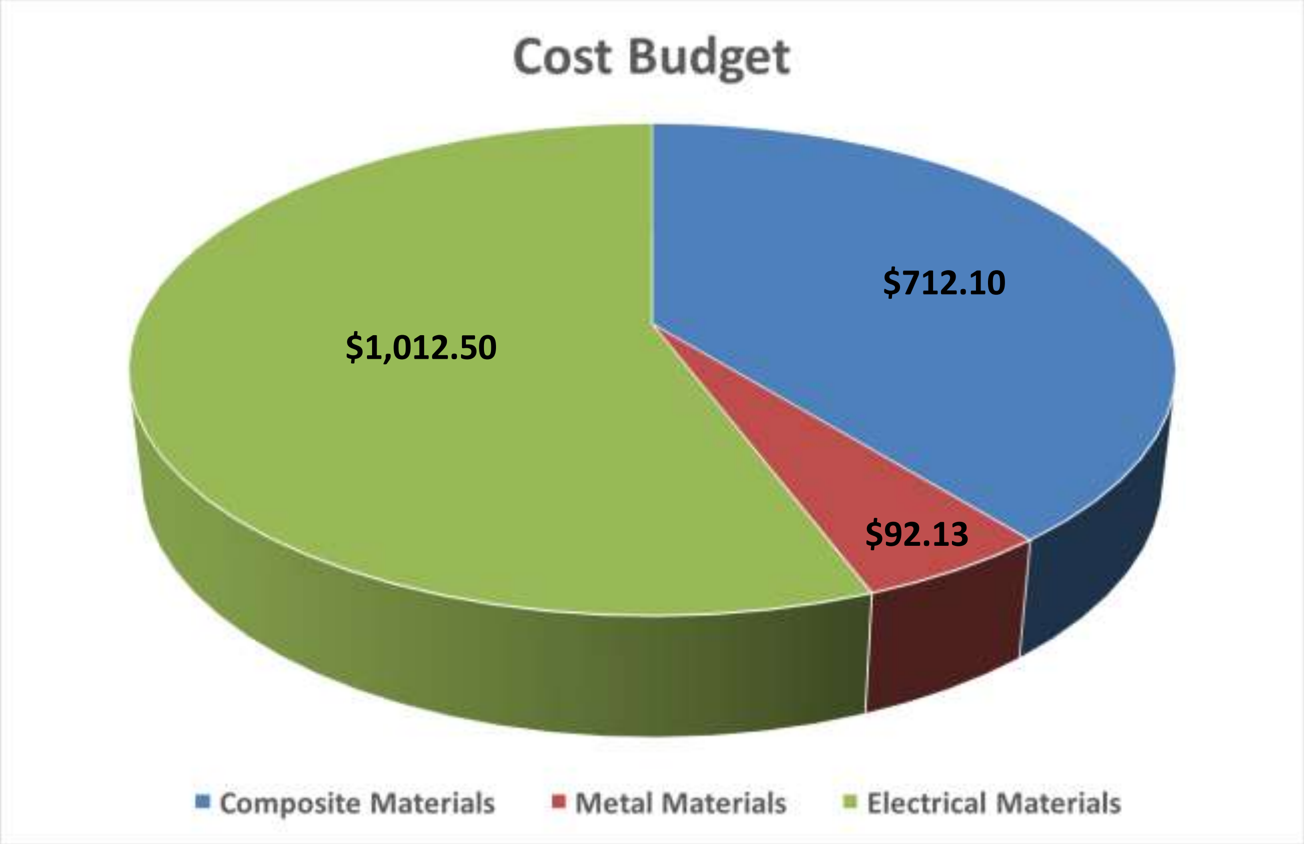


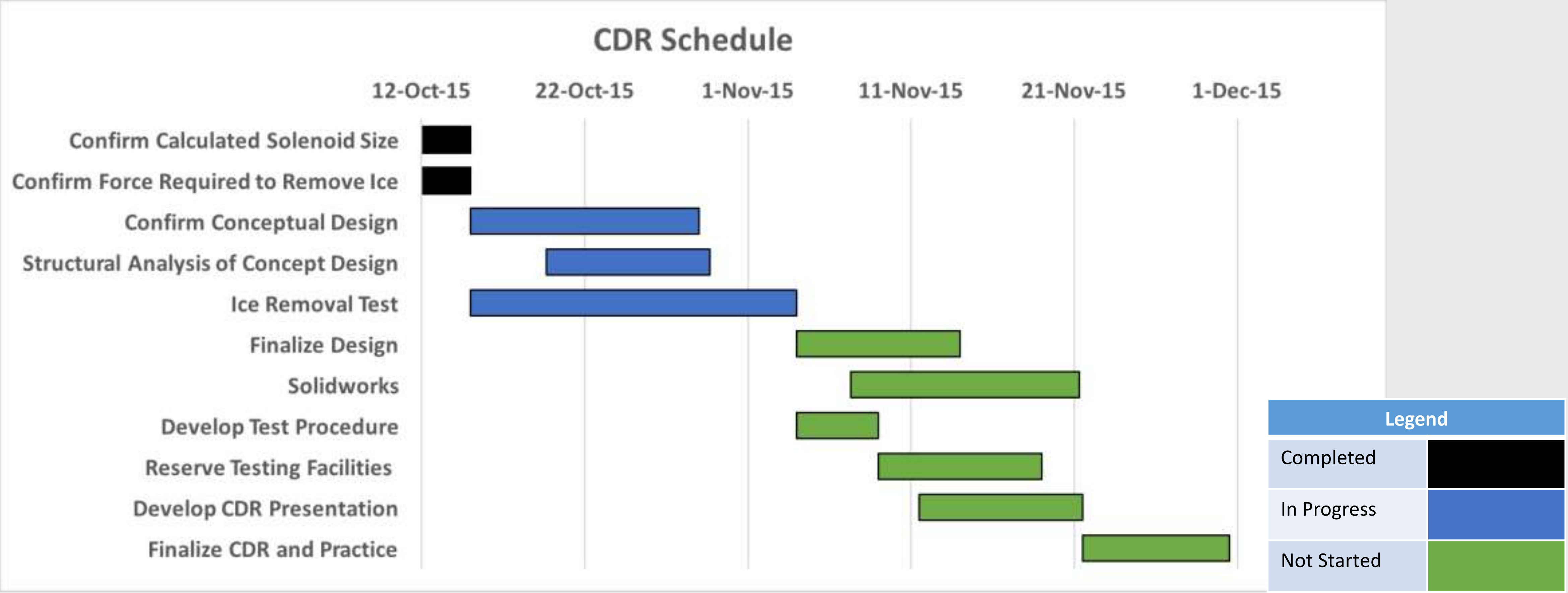
Figure 33. Cross-sectional view of solenoid.

Cost Budget

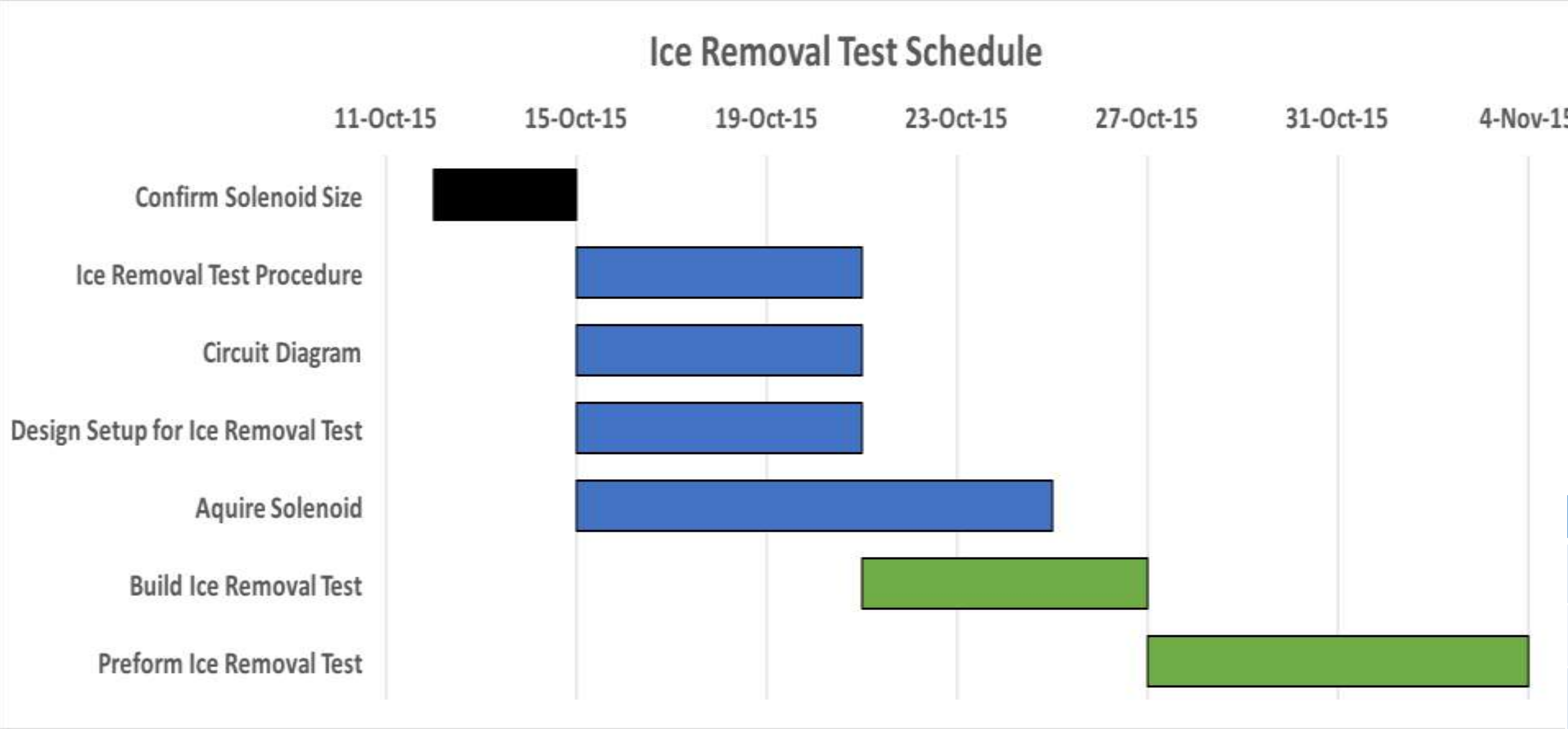


Total Cost: $1,816.73

Schedule


CDR Schedule
12-Oct-15
22-Oct-15
1-Nov-15
11-Nov-15
21-Nov-15
1-Dec-15
Confirm Calculated Solenoid Size
Confirm Force Required to Remove Ice
Confirm Conceptual Design
Structural Analysis of Concept Design
Ice Removal Test
Finalize Design
Solidworks
Develop Test Procedure
Reserve Testing Facilities
Develop CDR Presentation
Finalize CDR and Practice
Legend
Completed
In Progress
Not Started

Ice Removal Test Schedule



Legend	
Completed	⬛
In Progress	🟦
Not Started	🟩

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Questions?

Backup Slides

Design Requirements

- **FR.1** The full-scale system shall be integrable with the Orion UAV.
  - **DR.1.1** The full-scale system shall weigh less than 100 lb.
  - **DR.1.2** The de-icing mechanism shall be integrable with a DAE11 airfoil.
    - **DR.1.2.1** The test section chord shall be 36 in.
    - **DR.1.2.2** The internal components of the de-icing mechanism shall fit between the leading edge and half chord
  - **DR.1.3** The installation of the system shall not damage or degrade the structural integrity of the wing.
  - **DR.1.4** The operation of the system shall not damage or degrade the structural integrity of the wing.

Design Requirements

- **FR.2** The prototype shall remove ice.
  - **DR.2.1** The prototype shall be capable of removing ice built-up to 0.36 in thick on test section.
    - **SPEC.2.1.1** The ice shall cover the test section from the leading edge to 7% chord on the upper surface and 2% on the lower surface.
  - **DR.2.2** The prototype shall be capable of removing ice at any time during a five-day continuous flight.
  - **DR.2.3** The maximum allowable thickness of ice remaining at any point along the surface of the test section after the activation of the system shall be 0.1 in.

Design Requirements

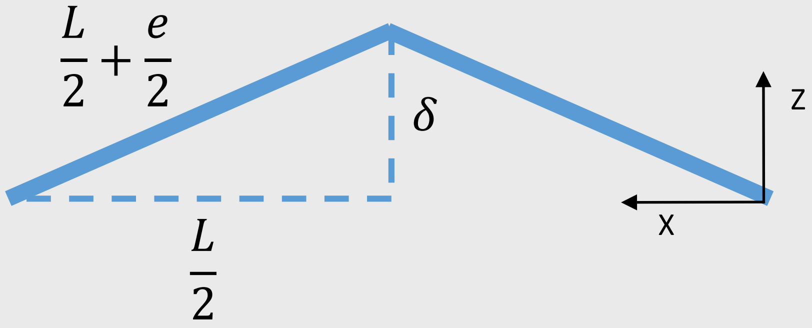
- **FR.3** The full-scale system shall use less than 4kW-hr to de-ice the wing section.
  - **DR.3.1** The prototype shall operate on an incoming 28 V DC voltage line.
  - **DR.3.2** The full-scale system instantaneous power draw shall be at most 2 kW.

- **FR.4** Integration of the de-icing mechanism with the test section shall not decrease the Lift to drag ratio of the test section by more than 10%.

Deflection Model Assumptions

Assumptions

- Ice will break in tension by modulus of fracture
- Ice will elongate by e in the x-axis
- Deflection of ice in the z-axis (δ) is determined by modeling ice as 2 flat plates



- Carbon fiber and ice will have the same deflection
- Force applied to carbon fiber is the force required to generate deflection

Deflection of Ice

Maximum tensile force: $F_{tension} = \sigma_{fracture} \cdot L \cdot d$

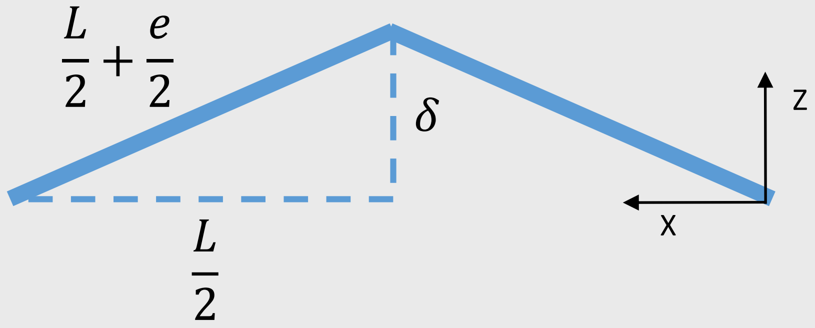
Young's Modulus of Ice: $E = 1 \cdot 10^3\ ksi$

Cross-sectional area: $A = d \cdot L$

Elongation of Ice: $e = \dfrac{F_{tension} \cdot L}{E \cdot A}$

Deflection of Ice: $\delta = \sqrt{\left(\frac{L}{2} + \frac{e}{2}\right)^2 - \left(\frac{L}{2}\right)^2}$

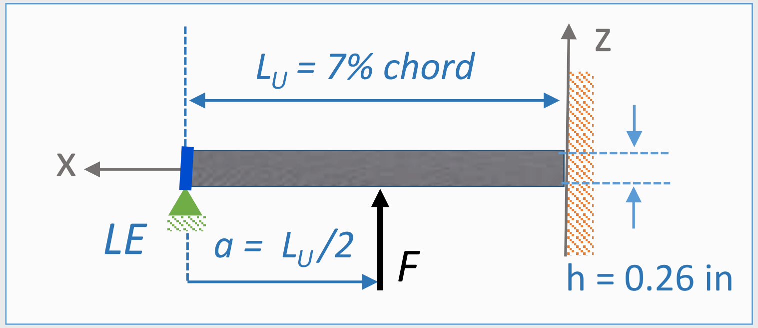
Surface	Maximum Tensile Force	Cross-sectional Area	Elongation of Ice	Deflection of Ice
Upper	$154.53\ lb$	$4.5\ in^2$	$4.12 * 10^{-4}\ in$	$0.0497\ in$
Lower	$44.44\ lb$	$4.5\ in^2$	$1.19 * 10^{-4}\ in$	$0.0267\ in$



Deflection of Wing Surface

Force to generate deflection δ	$F = \dfrac{\delta(3EI(3L^2 - a^2)^2)}{a(L^2 - a^2)^3}$
Bending moment from force F	$M_{b,max} = \dfrac{Fa}{2L^3}(L-a)^2(2L+a)$
Maximum Stress from Bending	$\sigma_{max} = \dfrac{L \cdot M_{b,max}}{I}$

Property	Maximum Stress from Bending (ksi)	Relation	Max Allowable Stress (ksi)	Feasible?
τ_U	45.6	>	7.68	NO
τ_L	23.4	>	7.68	NO
σ_U	749	>	51.2	NO
σ_L	402	>	51.2	NO



$$E = 46.4 \cdot 10^3\ ksi$$

$$I = \frac{bh^3}{12} = 5.12 \cdot 10^{-4}\ in^4$$

Fatigue Limit

Time between de-icing: **60 seconds**[A]

Number of pulses to remove ice: **3 pulses**

Lifetime requirement of de-icing mechanism:
3% of lifetime of aircraft = $0.03 \cdot 5000 = \mathbf{150\ \boldsymbol{hrs}}$

Total number of cycles required for lifetime of system:

$$150\ hr\left(\frac{60\ min}{1\ hr}\right)\left(\frac{3\ pulses}{1\ min}\right) = \mathbf{2.7 \cdot 10^4}\ \boldsymbol{cycles}$$

Stress amplitude ($\boldsymbol{\sigma_a}$): cyclic stress loading below which material will not fail before $\mathbf{10^7}$ **cycles**

For carbon fiber:
$\sigma_a = 14\% \cdot \sigma_{allowable} = 7.17\ ksi$

$\sigma_{U,calc} = 17.0\ ksi \rightarrow \sigma_{U,calc} > \sigma_a$

$\sigma_{L,calc} = 4.91\ ksi \rightarrow \sigma_{L,calc} < \sigma_a$

The upper surface will fail before 10^7 cycles. However, only 10^4 cycles are needed – 3 orders of magnitude less

Rectangular Solenoid Properties Calculations

Subject: Bottom solenoid must generate **F = 231.4 lb$_f$**

- Bottom requires more F than top, analysis to see if larger F is achievable

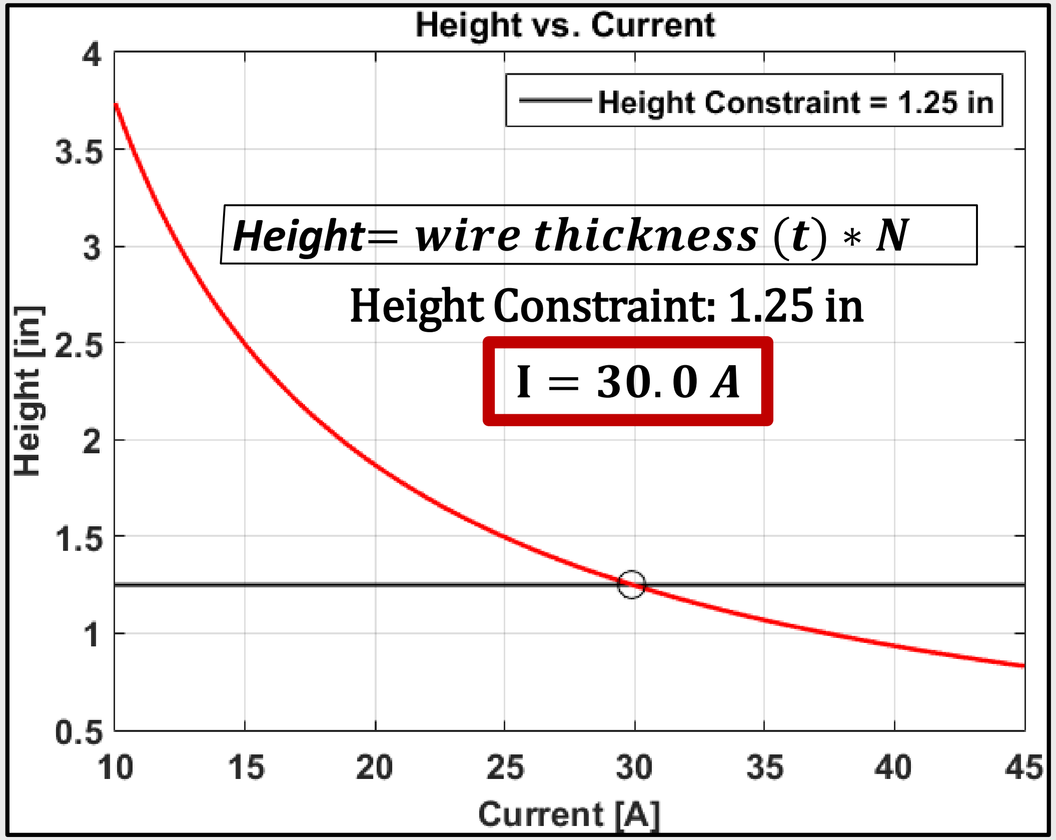
Assumptions:

  - A = 3 in^2 | d = 0.5 mm | t = 12 AWG copper wire
  - No energy loss due to heat & structural absorption
  - Negligible magnetic field interaction between solenoids
  - Instantaneous current draw
  - Weight of housing unit and electrical components neglected for now

Dependent Variables:

  - N - # of turns
  - I – Current draw from power source

$$\boxed{F = \frac{\mu_o N^2 I^2 A}{d^2}}$$



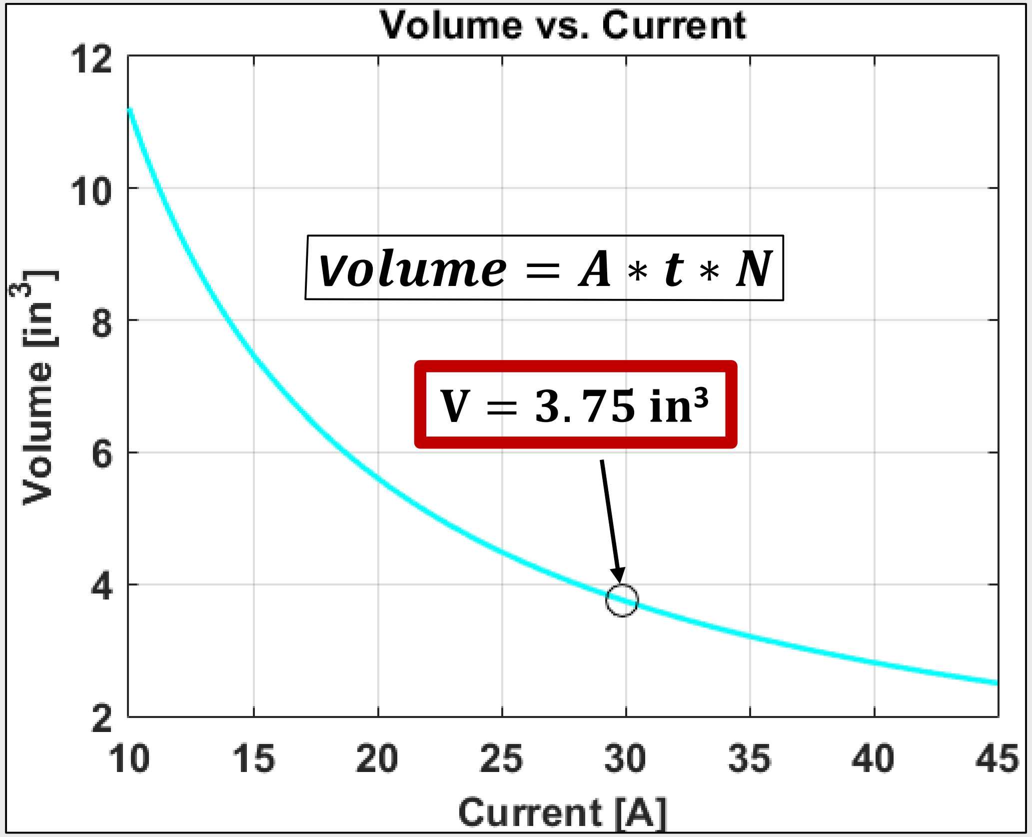
$\boxed{Height = wire\ thickness\ (t) * N}$

Height Constraint: 1.25 in

$\boxed{\mathbf{I = 30.0}\ A}$

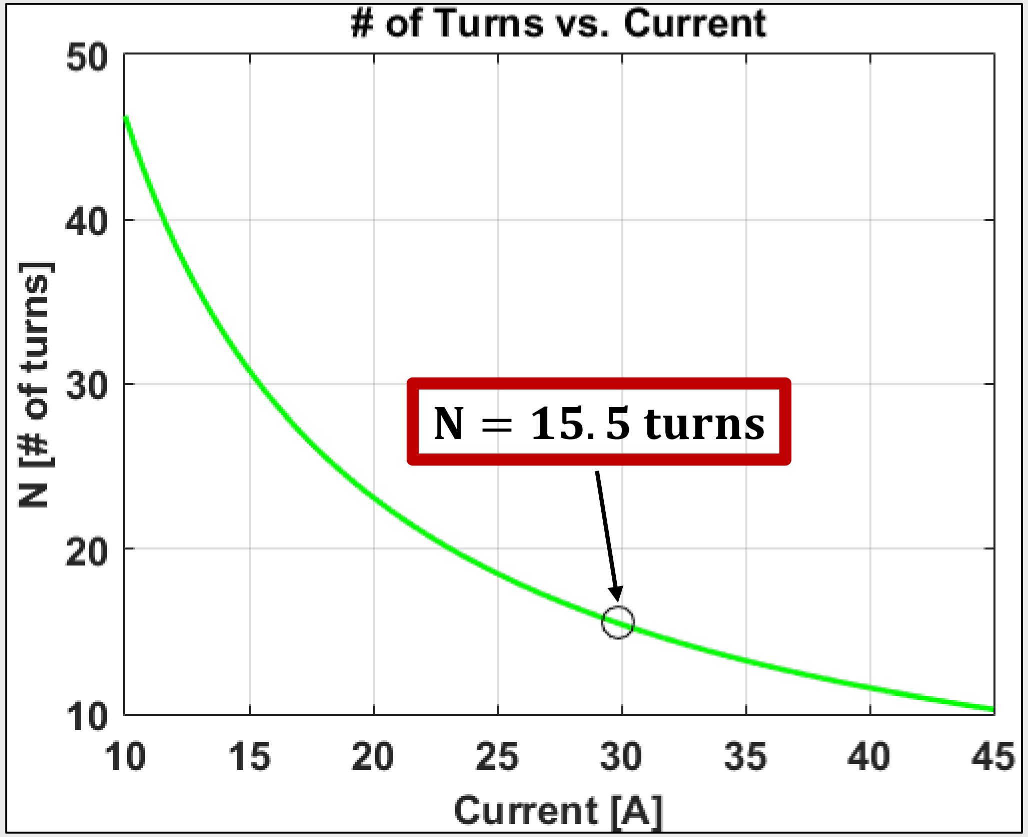
Project Description | Baseline Design | **Baseline Feasibility** | Project Status

Rectangular Solenoid Properties Calculations



$$Volume = A * t * N$$

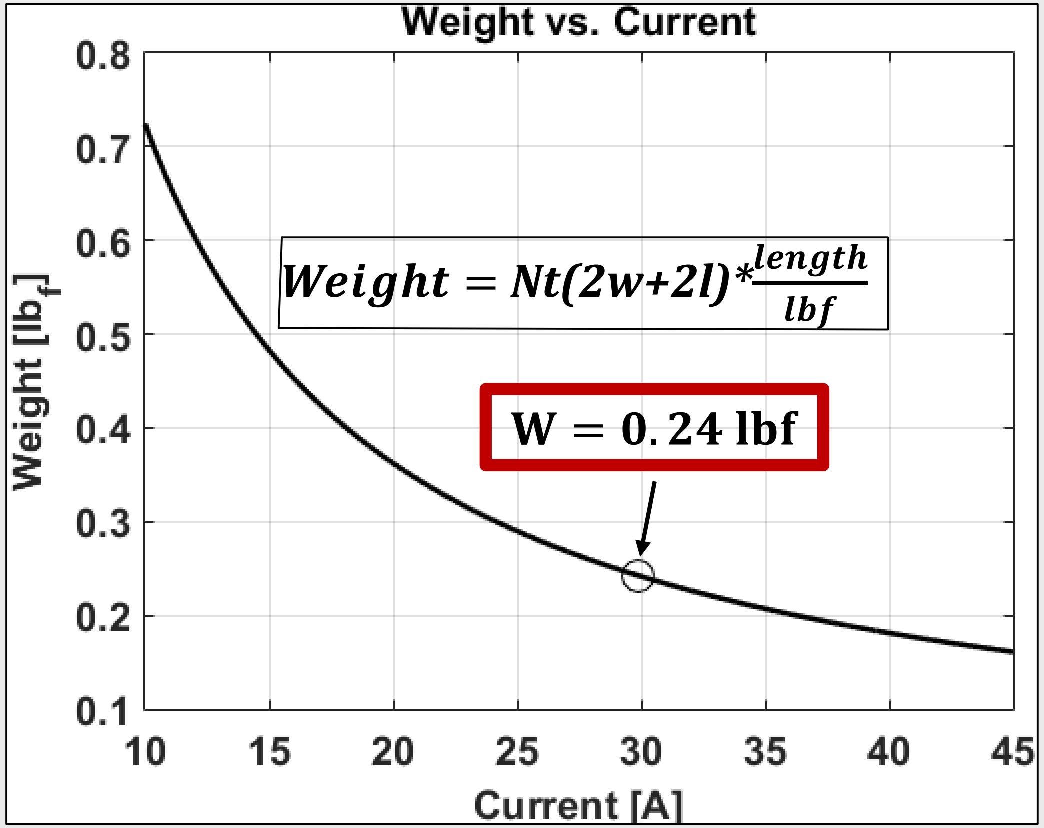
$$\boxed{\mathrm{V} = 3.75\ \mathrm{in}^3}$$



$$\boxed{\mathrm{N} = 15.5\ \mathrm{turns}}$$

Project Description | Baseline Design | **Baseline Feasibility** | Project Status

Rectangular Solenoid Properties Summary



Solenoid Requirements to generate *$F = 231.4\ lb_f$* :

Property	Value
Cross Sectional Area – A	3 in^2
Distance – d	0.0394 in (0.5 mm)
Thickness of wire – t	12 AWG (0.0808 in)
Height – h	1.25 in
Instantaneous Current – I	30.0 A
Volume – V	3.75 in^3
# of turns – N	15.5
Weight - W	0.24 lb_f

Cost Budget (Backup)

Item	Amount	Cost per	Total Cost
Composite Materials			
Carbon Fiber	1	$170.00	$170.00
Peel Ply	1	$37.00	$37.00
Breather	1	$25.00	$25.00
Vacuum Bag	1	$35.00	$35.00
Nomex Honeycomb	1	$120.00	$120.00
Quick Lock Seals	1	$36.00	$36.00
EPS Foam	1	$21.00	$21.00
Flexible Polyethyline	1	$20.00	$20.00
Layup Foam	3	$32.60	$97.80
Resin and Hardner	1	$93.00	$93.00
Thin Plyable Plastic	1	$6.90	$6.90
Bees Wax	1	$5.00	$5.00
Fastners	1	$6.47	$6.47
Silicone Sealent	1	$3.98	$3.98
Wood	1	$34.95	$34.95
		Total Section Cost	$712.10
Metal Materials			
Metal to Composite Epoxy	1	$62.00	$62.00
Alclad 2024-T3	1	$30.13	$30.13
		Total Section Cost	$92.13
Electrical Materials			
Solenoids	4	$200.00	$800.00
Wire	4	$8.25	$33.00
Capacitors	1	$70.00	$70.00
Arduino	1	$25.00	$25.00
Transformer	1	$4.50	$4.50
Power inverter	1	$80.00	$80.00
		Total Section Cost	$1,012.50
		TOTAL COST	**$1,816.73**

Mass Budget

Mass budget for full-scale Orion UAV assumes…

- 1 ft distance between solenoids on upper & lower surfaces
- 8 solenoids per circuit (1 circuit every 4 ft in spanwise direction)

Item	Weight for 1 Item [lb]	Quantity	Total Weight for Item(s) [lb]
Upper solenoid	0.25	125	31.5
Lower solenoid	0.25	125	31.5
Copper Wire (Upper & Lower Surface, Full Span) [A]	24.33	1	11.4
Aluminum Patch (Top & Bottom = 1 set)	0.35	65	21.9
Arduino	Negligible	1	0
DPDT	Negligible	1	0
Charger[B]	0.2	1	0.2
		Total weight for full-scale system:	**81.5 lb**

Max Weight Full-Scale = 100 lb → **81.48% of Allowable Weight Used**

Power Budget

Find Total Energy Consumption

Assumptions

- 2 kw battery over 2 hours flight, 2 ft wing span test section
- Linear ice formation (3”/hour), 0.36”/t_f = 0.36”/432 s
- Linear power distribution along the wing, P_s = 15.15 W/ft
- 4 solenoids produce the same force
- 1mm deflection of bending on the metal plate
- 3 pulses as a working cycle shall remove ice completely
- 10 % of charging and discharging efficiency

ϵ_a : 0.465 J

ϵ_c : 83.20 J

ϵ_T : 832 J

Total energy required: $E = 3N\epsilon_T + \epsilon_a \approx 3N\epsilon_T$

Energy occupation ratio (3 pulses as 1 working cycle): $\lambda = \frac{1}{1+\frac{P_s t_f}{3\epsilon_T}} = 16.0\%$

Power Budget Calculations

Arduino over 2 hours: $\epsilon_a = V_a I t = 5V * 46mA * 2h = 0.465\, J$

Energy stored in capacitor (1 pulse):

$$\epsilon_c = \epsilon_{eff} + \epsilon_{loss} = \eta\epsilon_c + (1-\eta)\,\epsilon_c$$

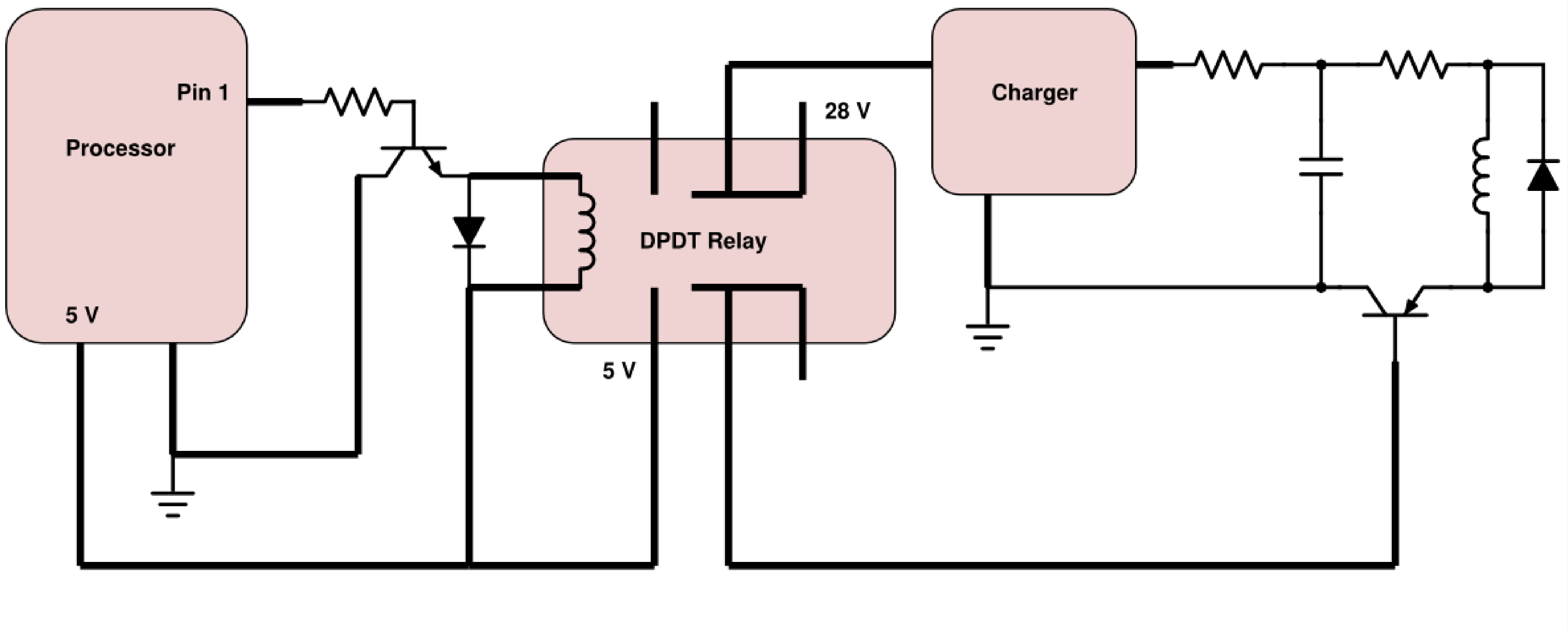
For η = 10% (4 solenoids):

$$\epsilon_c = \frac{\epsilon_{eff}}{\eta} = \frac{\eta C V^2}{2\eta} = \frac{2Fd}{\eta} = 10 * 2 * (1041.15\, N * 4) * 1mm = 83.2\, J$$

Total energy for charging a capacitor ($\eta = 10\%$) :

$$\epsilon_T = \frac{\epsilon_c}{\eta} = 10\ * 83.2 = 832\, J$$

Circuit Diagram



Mechanism Availability

Commercially available solenoids

Solenoids and inductors are readily available for purchase in thousands of variations.

Relatively cheap ~ $100

Low lead time

Manufacturing Materials Access

- Structural materials such as carbon fiber fabric, Nomex® Honeycomb, epoxy, and aluminum are all available to order online.
- Layup materials such as peel ply, breather, vacuum bags, and quick lock seals are also available online.

Ice Casting Details

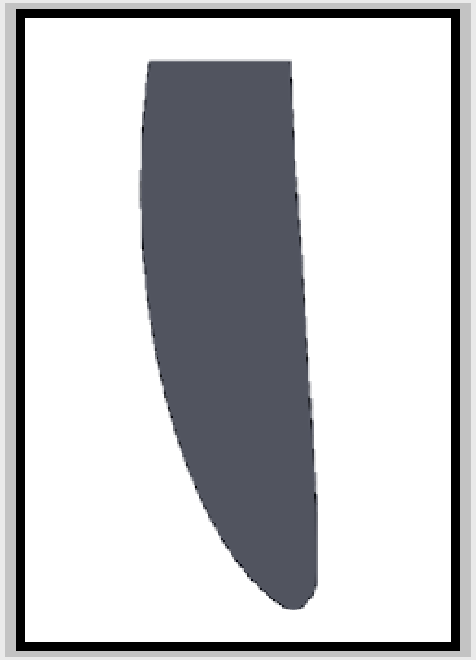
Assumptions:

- Ice will expand in the path of least resistance.
- Team will not fill trough completely to allow for ice expansion and avoid cracks in the ice.

Feasibility Results:

- The trough can be manufactured a long with the two end caps.
- Price = \$21 (EPS Foam) + \$20 (bendable plastic, smooth layer) = \$41

Both cost and manufacturing are possible with the resources that the team has. This means that ice casting is a feasible aspect of our project.



End cap with engraved DAE 11