Aerospace Engineering

Aurora FLIGHT SCIENCES

AESIR

University of Colorado at Boulder

Actuated Electromagnetic System for Ice Removal

Test Readiness Review
March 2, 2016

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Overview

Problem Statement & Objectives

Design, build, and test a small-scale prototype of a deicing system for the Orion UAV.

Orion UAV

Functional Requirements

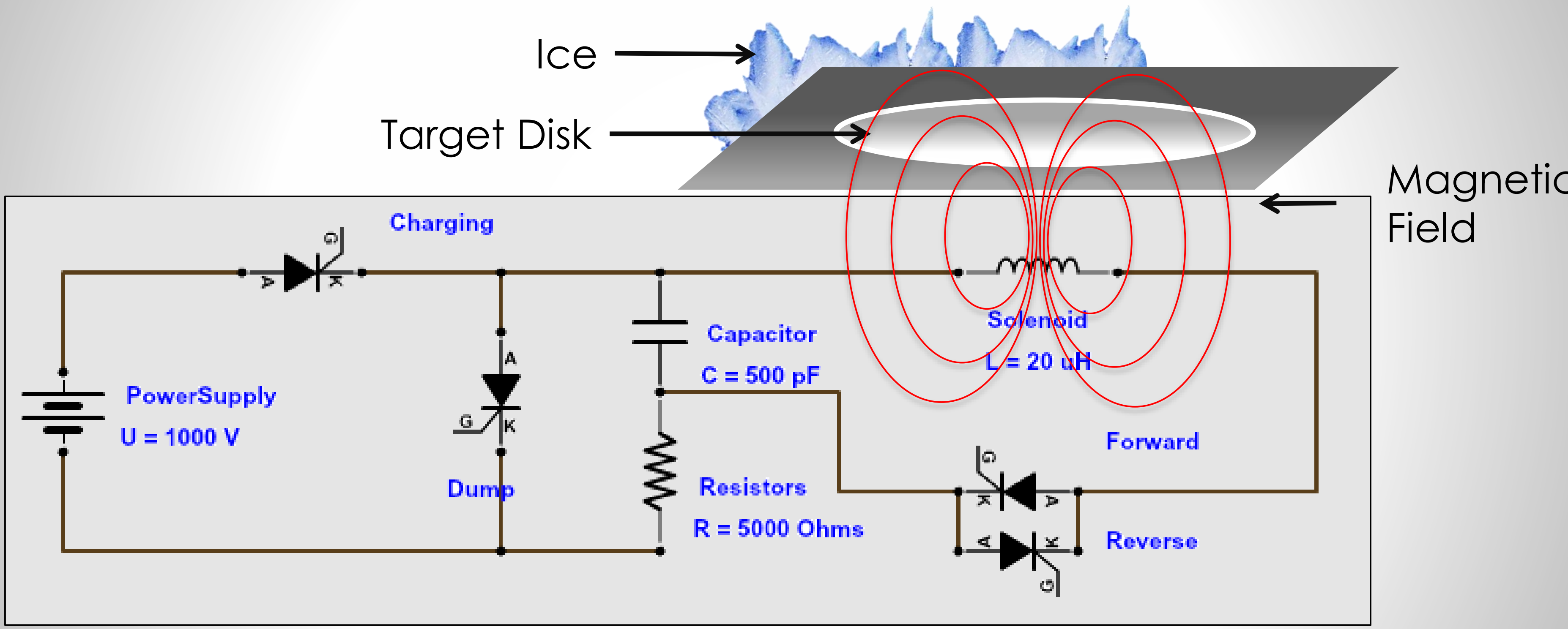
FR.1 - The full-scale system shall be **integrable with the Orion UAV**.

FR.2 - The prototype shall **remove ice**.

FR.3 - The full-scale system shall use **less than 4kW-hr to deice** the wing section.

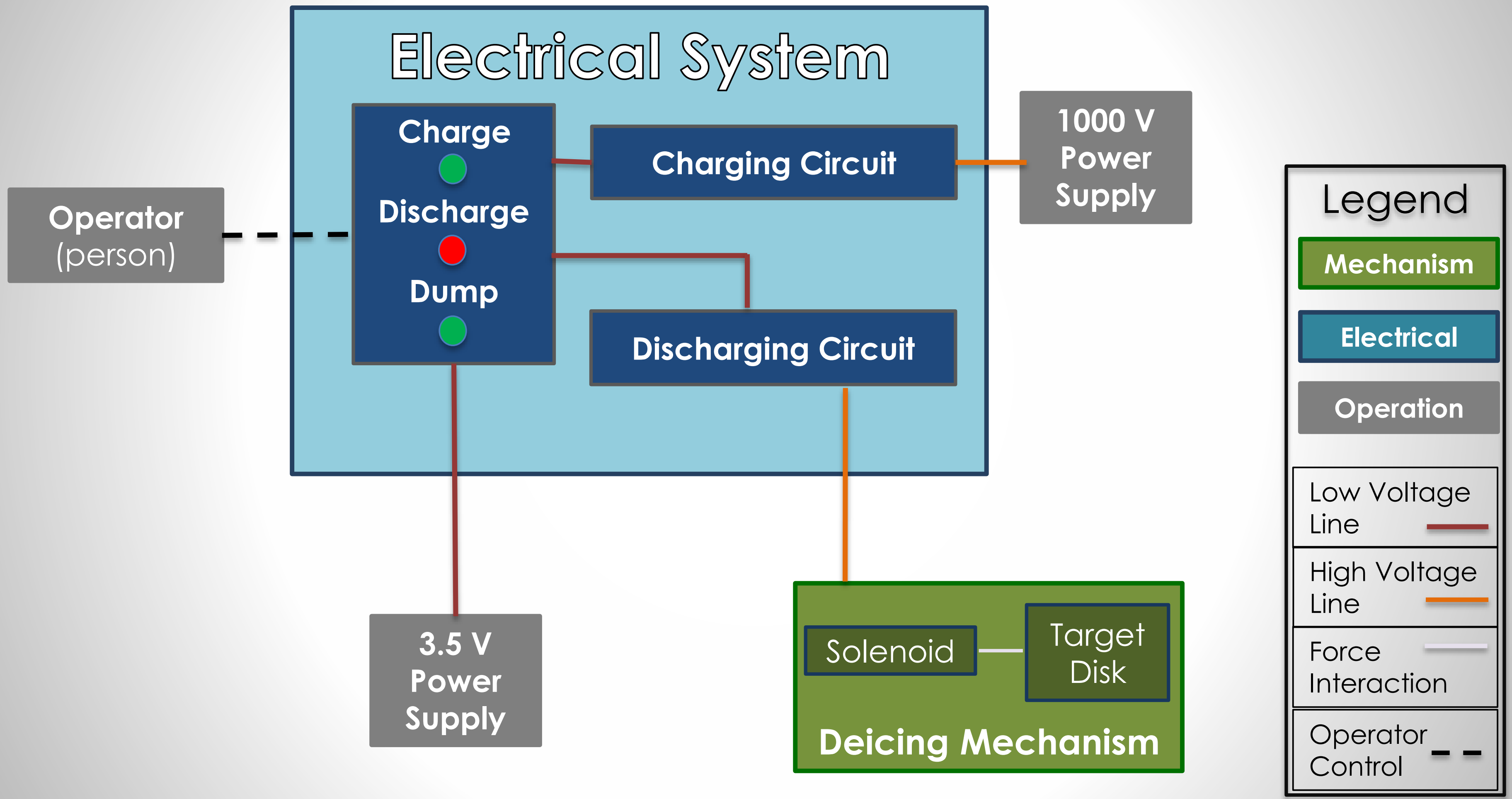
Design Overview

Electromagnetic Deicing Mechanism



Deicing Mechanism = Baseline design used for all levels of success

Functional Block Diagram

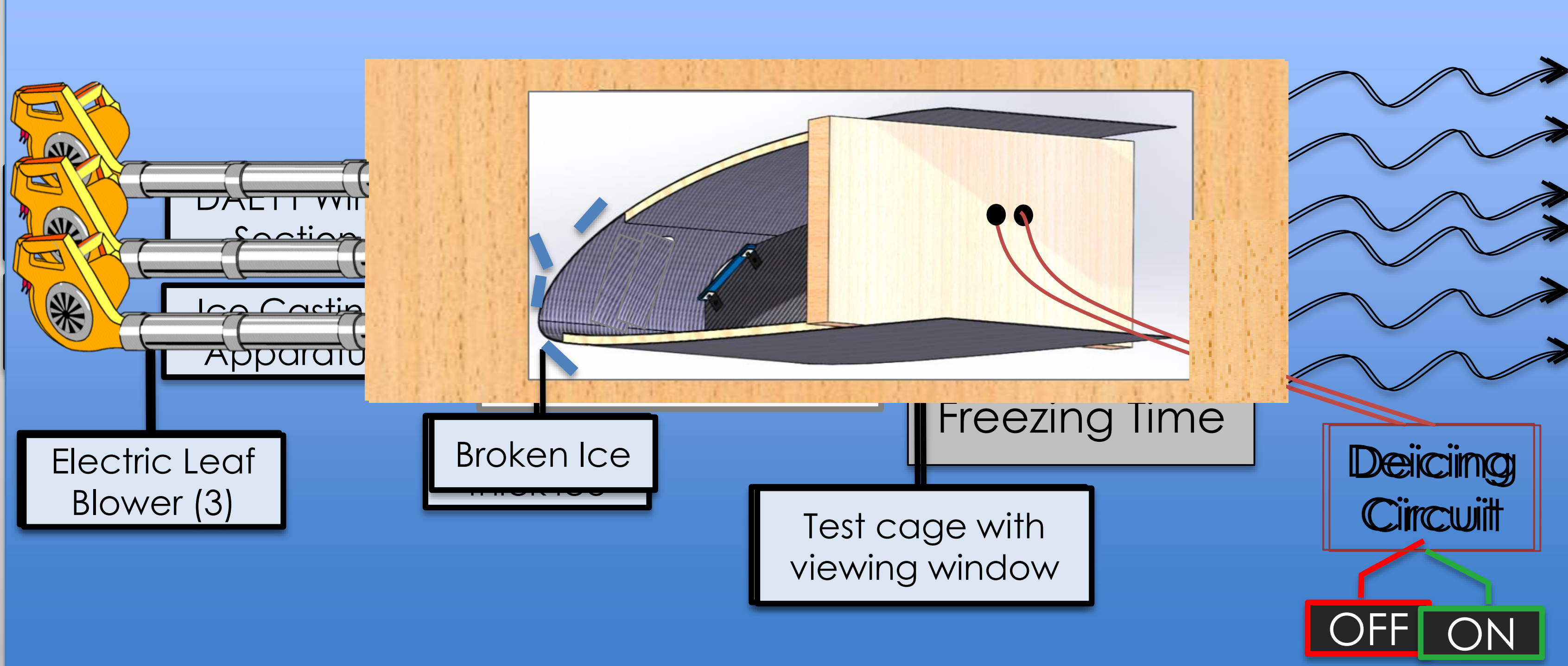


Concept of Operations

Purpose of Level 3:

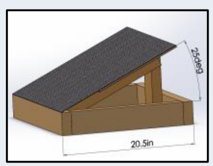
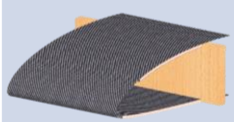
- Integration into wing structure-like Orion UAV
- Testing in flight-like wing section and conditions

Ice Testing Occurs in Freezer $(-11^{o}F)$



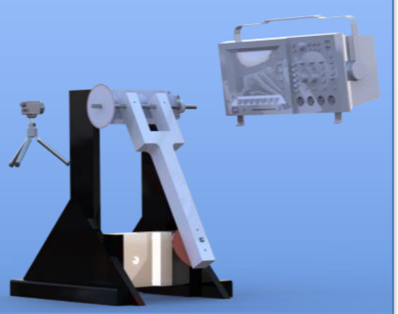
Levels of Success

Deicing Mechanism = Baseline design used for all levels of success

Level of Success	Description		Corresponding Tests	Level of Success Achieved when…
1	Deicing mechanism integrated with **ballistic pendulum**	 Ballistic Pendulum	• Ballistic Pendulum Tests	**Solenoid Force Model verified**
2	Deicing mechanism integrated with **carbon fiber flat plate**	 Flat Plate	• Deflection tests • Deicing tests in simulated flight conditions	**ANSYS Model verified. Ice broken from flat plate**
3	Deicing mechanism integrated with **carbon fiber full wing section**	 Full Wing Section	• Deflection tests • Deicing tests in simulated flight conditions	**Ice broken from wing section in simulated flight conditions**

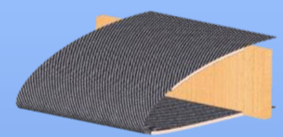
Critical Project Elements

Ballistic Pendulum

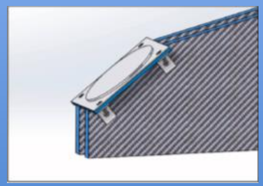


Pendulum Assembly

Wing Section

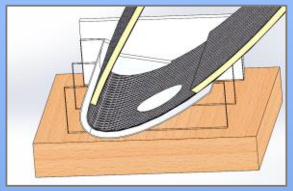


Test Section

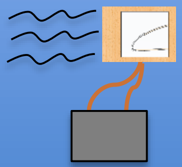


Housing Unit & Support Structure

Test Setup



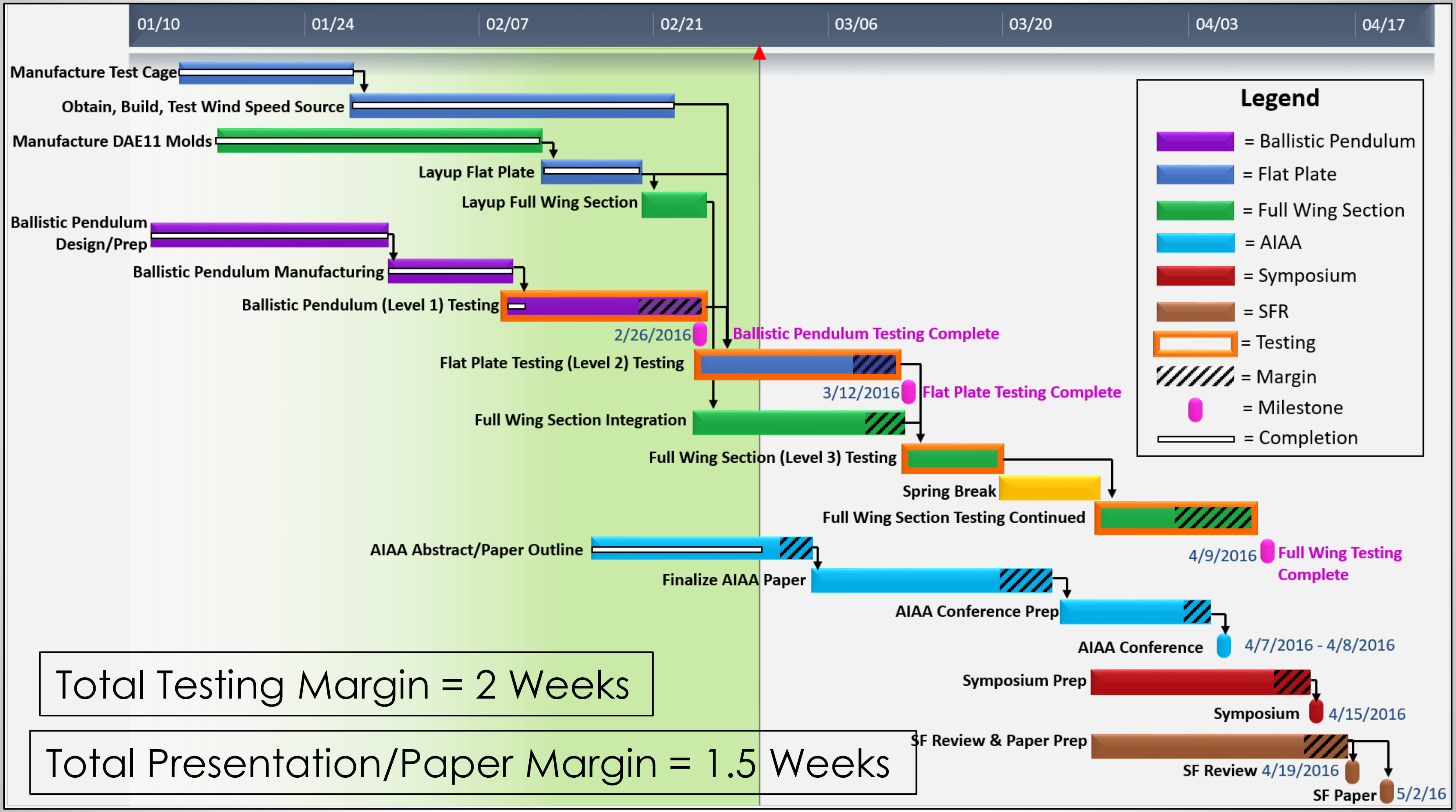
Ice Casting



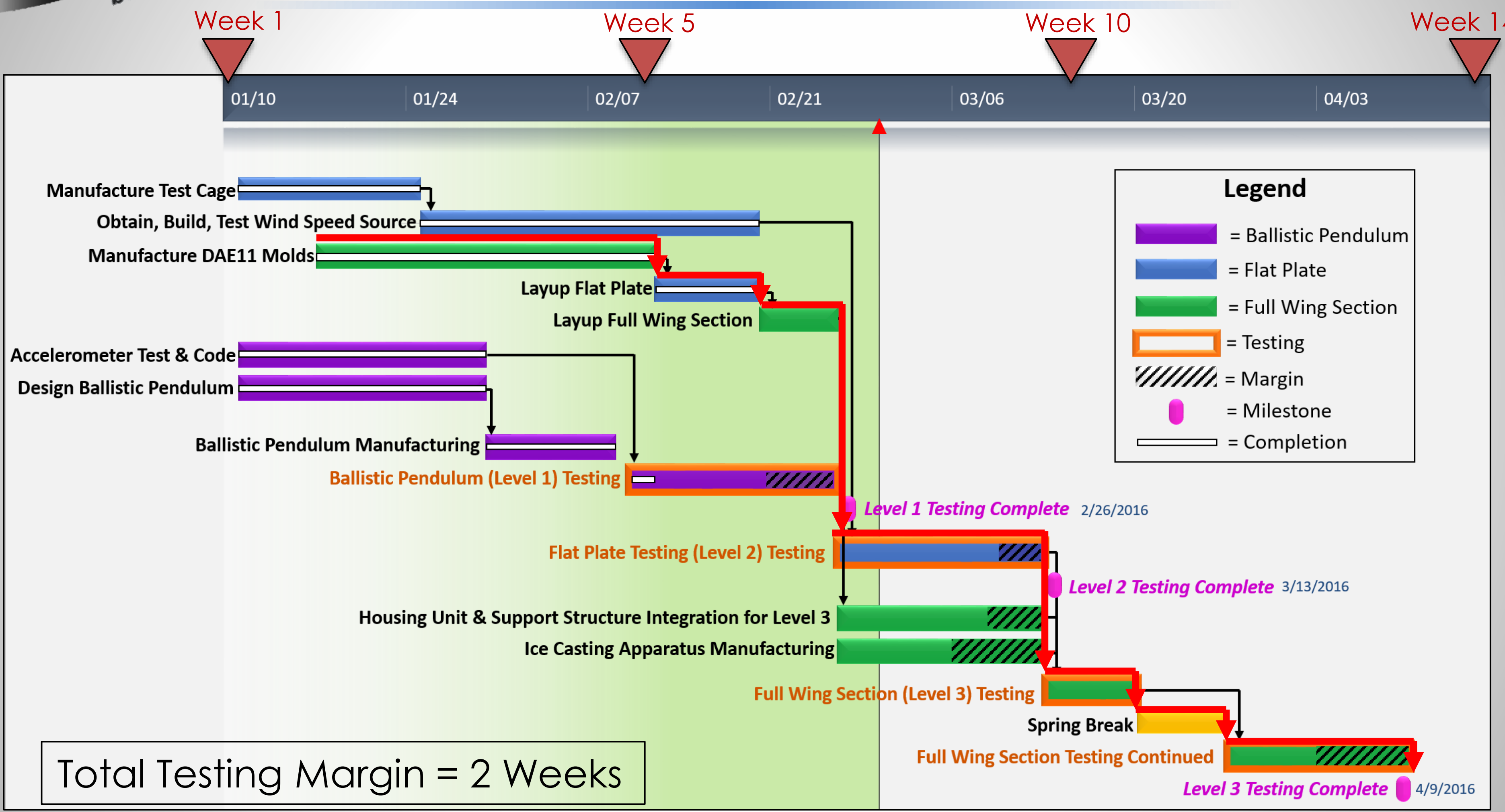
Wind Speed & Test Cage

Schedule

Overall Schedule



Test-Focused Schedule



Total Testing Margin = 2 Weeks

Test Readiness

Test Readiness Roadmap

Test 1 – Ballistic Pendulum Test (Complete by: 2/26)

→ Validate solenoid force model

Test 2 – Flat Plate Deflection Test (Complete by: 3/13)

→ Validate flat plate ANSYS model by measuring deflection of flat plate

Test 3 – Flat Plate Wind Cage Ice Test (Complete by: 3/13)

→ Verify ice in ANSYS model by breaking ice off flat plate

Test 4 – Full Wing Section Deflection Test (Complete by: 4/9)

→ Validate wing section ANSYS model by measuring deflection of wing section

Test 5 – Full Wing Section Wind Cage Ice Test (Complete by: 4/9)

→ Break ice off wing section, prove overall functionality

Ballistic Pendulum Overview

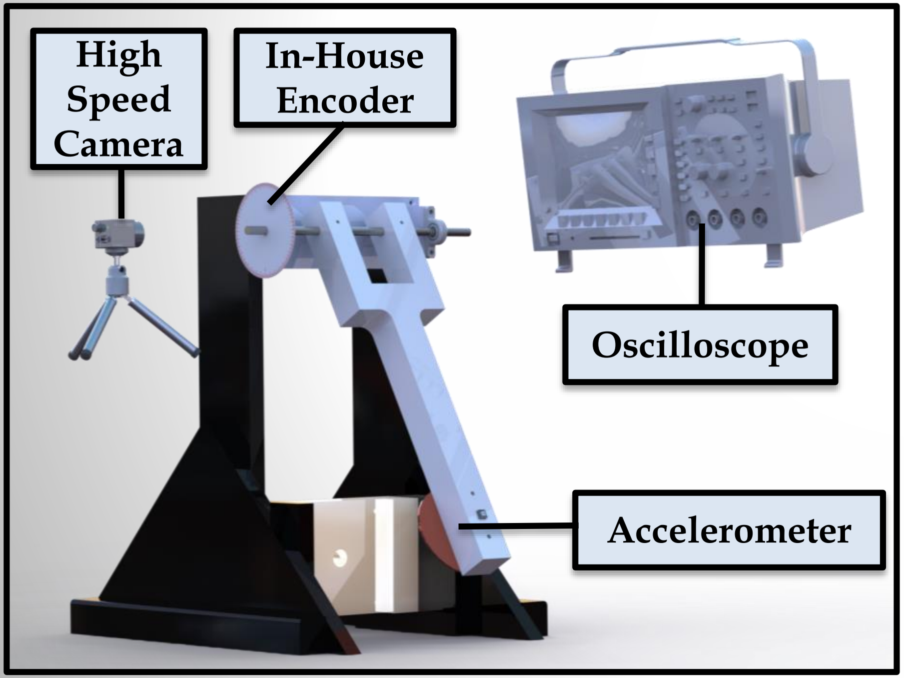
Purpose

- Verify solenoid force model
- Validate design

Requirements Verified

- DR.2.1 The deicing mechanism shall be capable of **removing 3/8 in thick ice** on test section
- DR.3.1 The deicing mechanism shall operate on an **incoming 28 V DC voltage line**.
- DR.3.2 The full-span system **instantaneous power draw shall be at most 2 kW**.

Ballistic Pendulum Test Setup

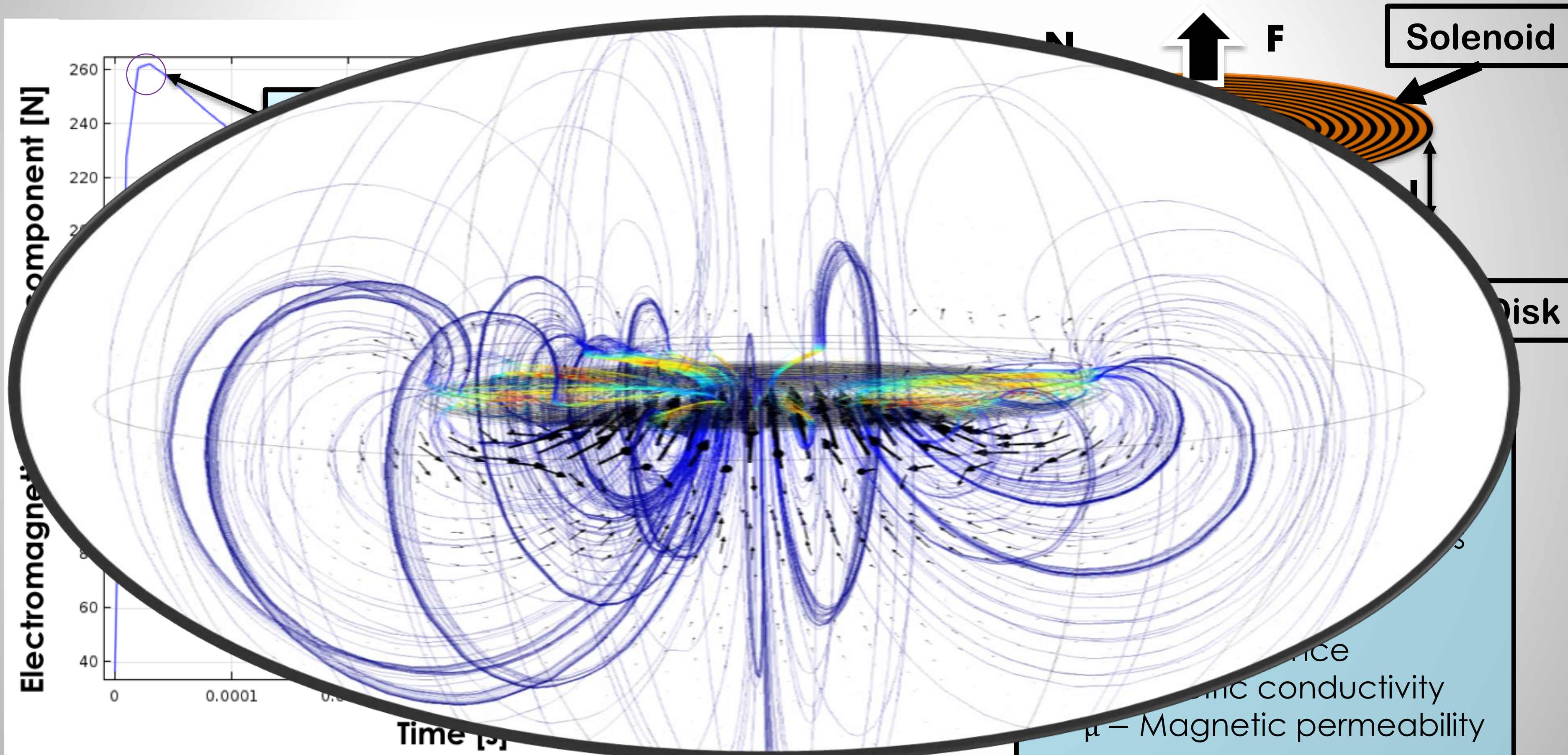


2 Methods to Calculate Solenoid Output Force

Measure		Calculate
Acceleration (Accelerometer)	→	Force (via torque, conservation of energy)
Max Angle (In-House Encoder)	→	Force (via conservation Of angular momentum)

Recall: Solenoid Force Model Derivation

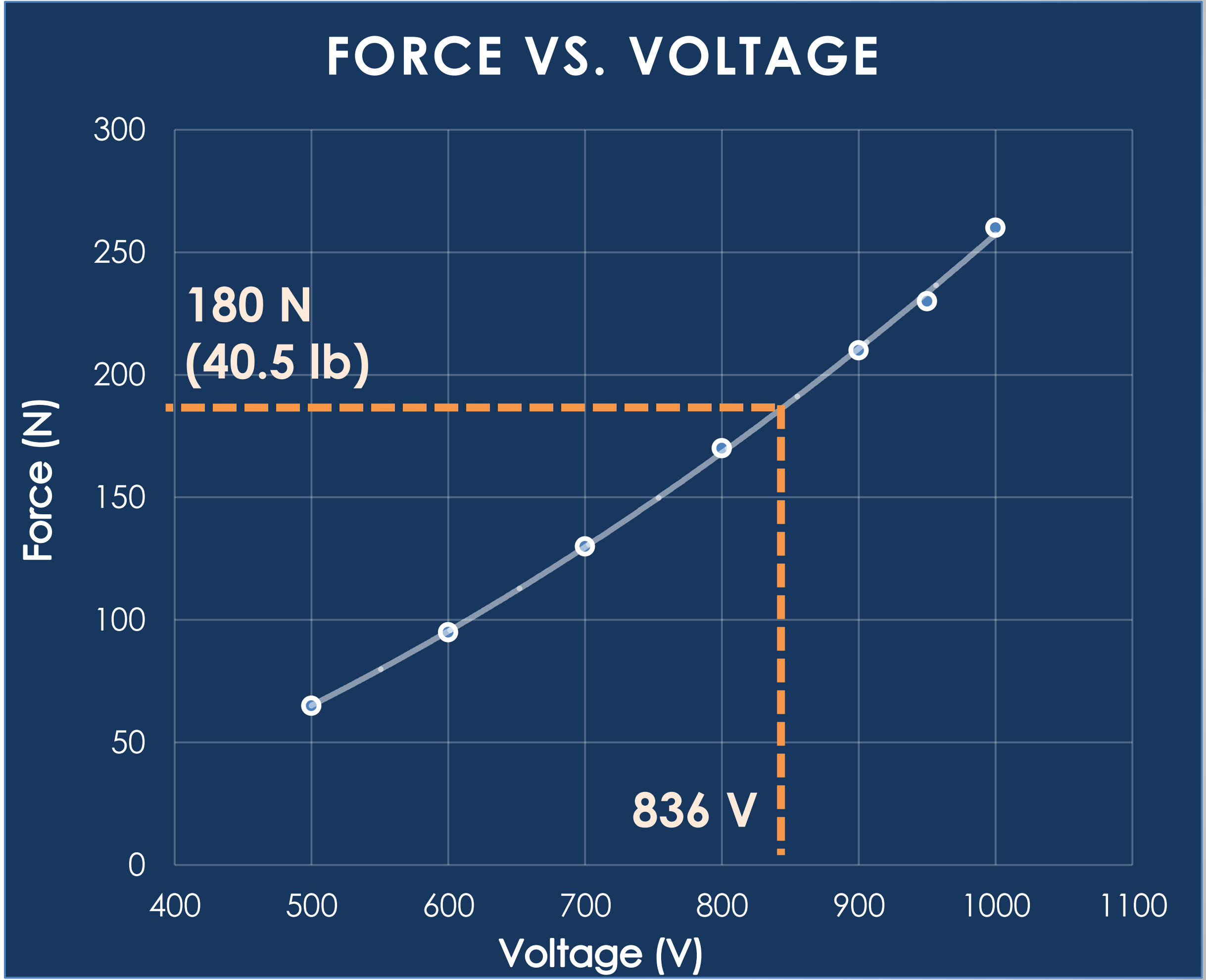
Goal: Determine max impulsive force from solenoid using COMSOL model



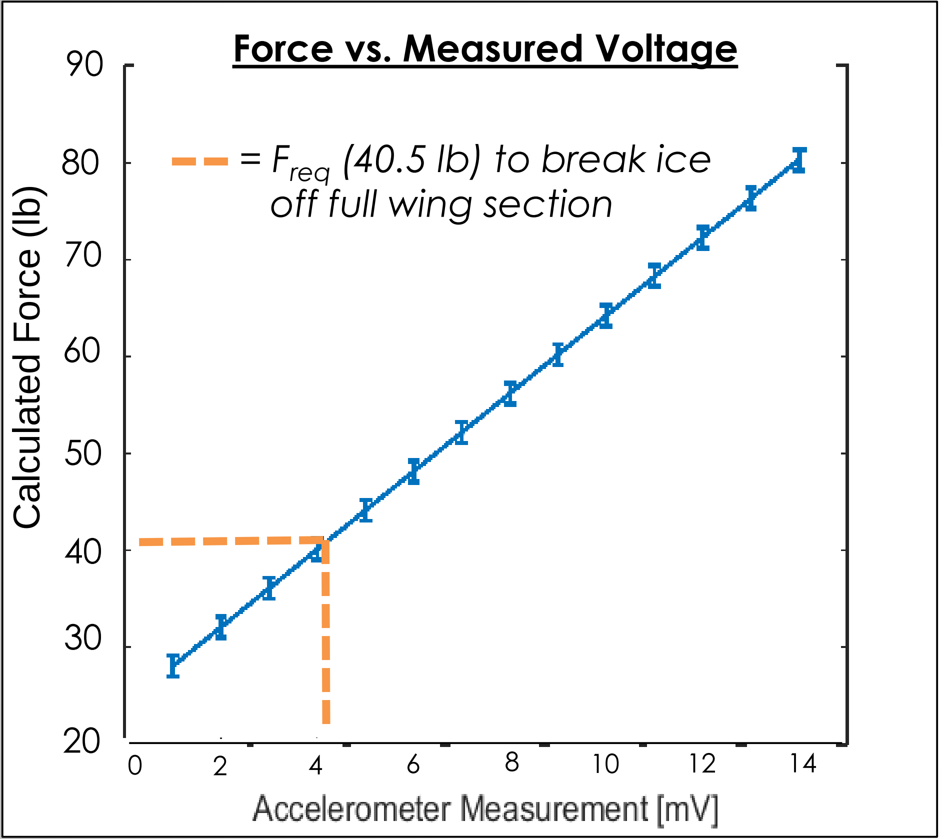
Solenoid Force Model

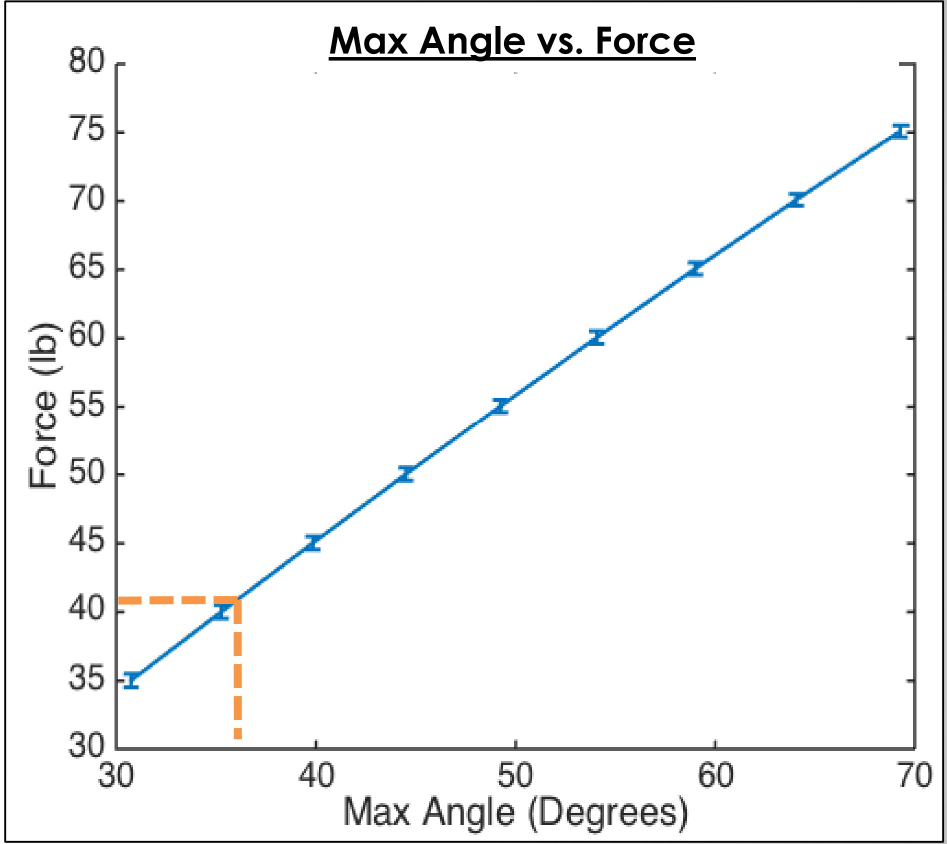
Copper Solenoid Parameter	Value
Outer diameter	3.000 in
Inner diameter	0.039 in
Height	0.190 in
Wire thickness	0.030 in
Average gap between wire loops	0.007 in
Number of turns	36

Copper Target Disk Parameter	Value
Gap distance	0.078 in
Disk thickness	0.078 in
Disk Diameter	4.000 in



Solenoid Force Model & Predicted Results





Accelerometer Sensitivity: 1.0 mV/g
→ Force Uncertainty: **+ 2.4 lb**

In-House **Encoder Uncertainty**: 0.1°
→ Force Uncertainty: **+ 0.47 lb**

Flat Plate Deflection Test Overview

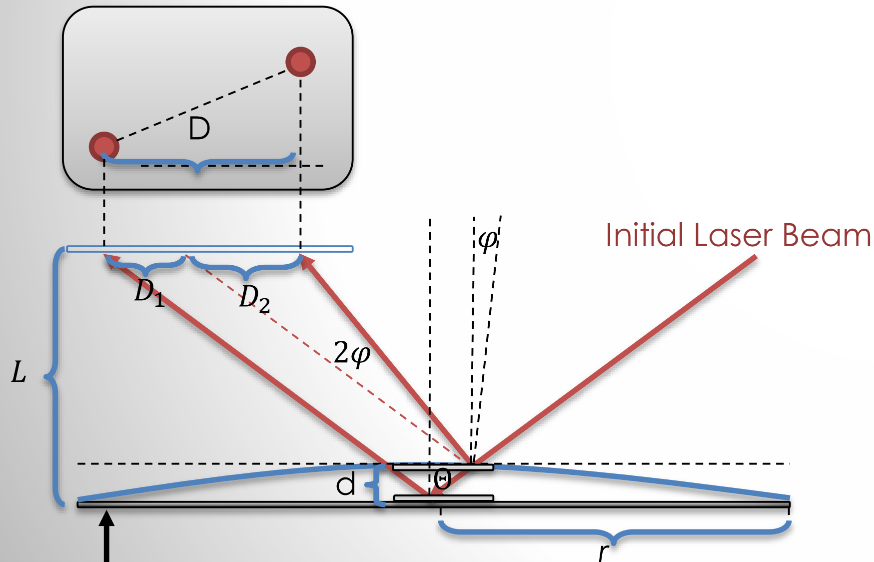
Purpose

- Verify ANSYS deflection model with measured deflection

Requirements Verified

- DR.1.3 Operation of the deicing mechanism shall **not damage or degrade the structural integrity** of the wing
- DR.2.1 The deicing mechanism shall be capable of **removing 3/8 in thick ice** on test section

Flat Plate Deflection Test Setup



Cross-sectional view of carbon fiber flat plate

Flat Plate Deflection Testing (Complete by:)

Measure		Calculate
Distance traveled by laser (D)	→	Deflection of flat plate (via geometry)

Testing Location: Thorlabs

Recall: Flat Plate Analysis & ANSYS Model

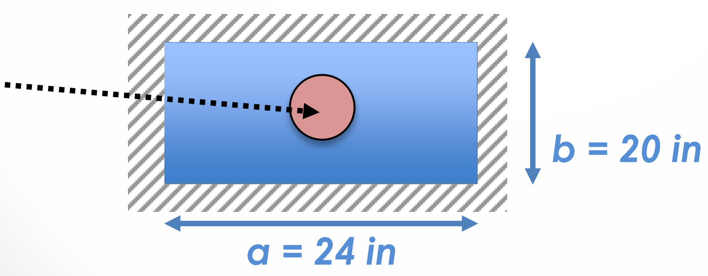
- Flat Plate ANSYS Model- calculates deflection of carbon fiber, force necessary to break ice thickness
- To Check model: Back of the Envelope Deflection for Flat Plate
  - from Roark's Formulas
- Full model validation to occur with deflection and ice break testing

Back of the Envelope Assumptions
- Thickness = uniform, 0.09 in carbon fiber with 3/8 in thick honeycomb
- Force acts on center of plate
- Fixed Boundary Conditions on all sides

$$y_{max} = \frac{\alpha W b^2}{E t^3}, \quad \alpha \approx 0.0706$$

(appr. from a/b = 1.2)

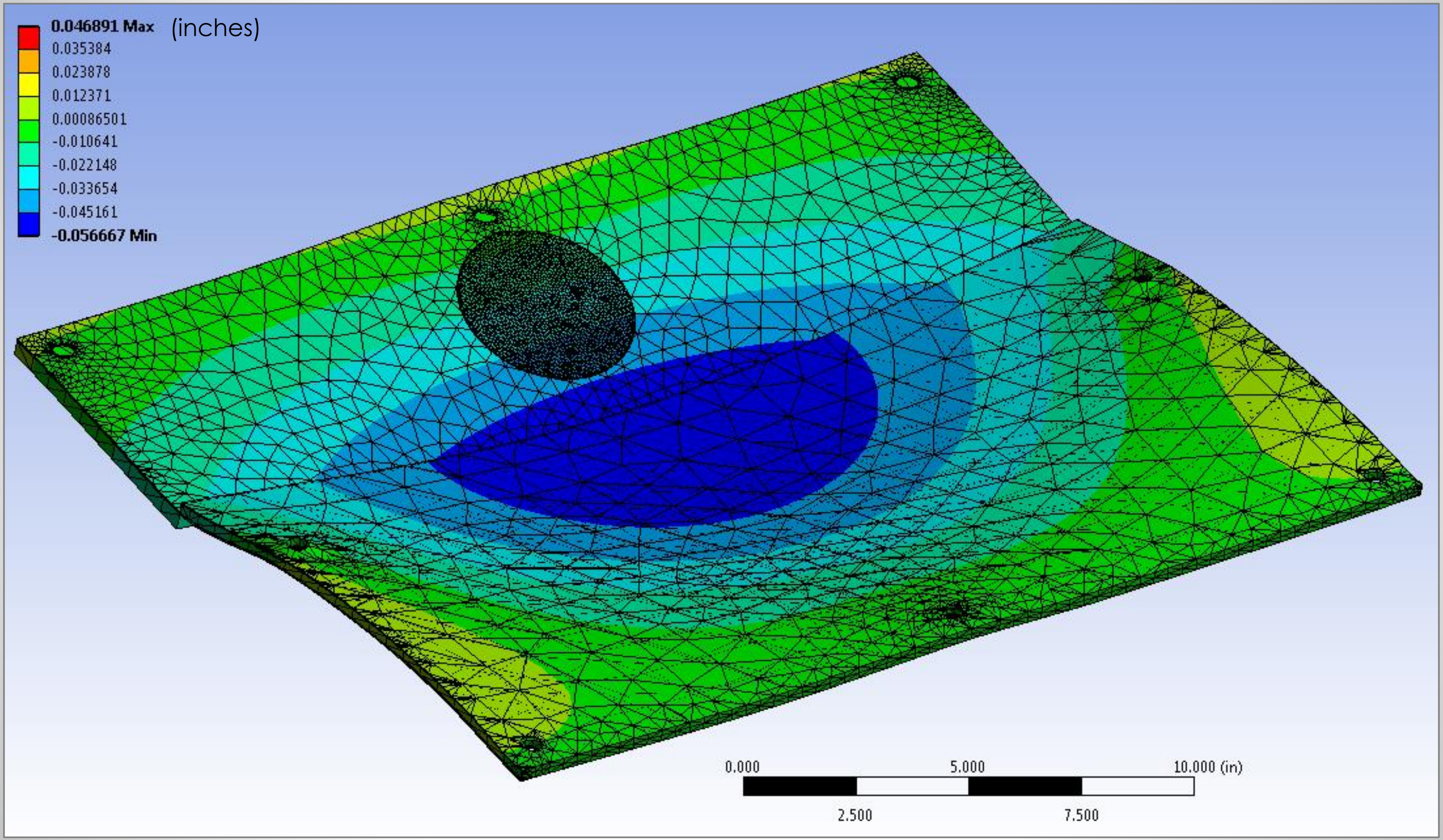
Force, *W*, applied over circular region



$$y_{max,calc} = 0.008\ in$$

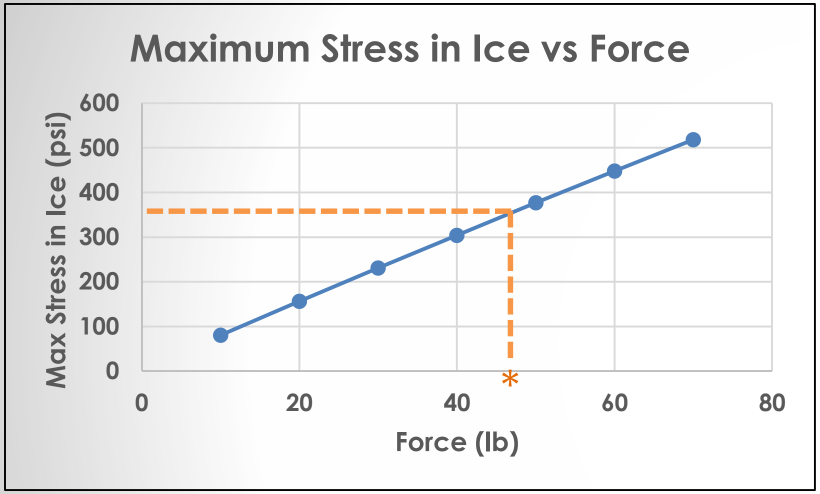
$$y_{max,ANSYS} = 0.05\ in$$

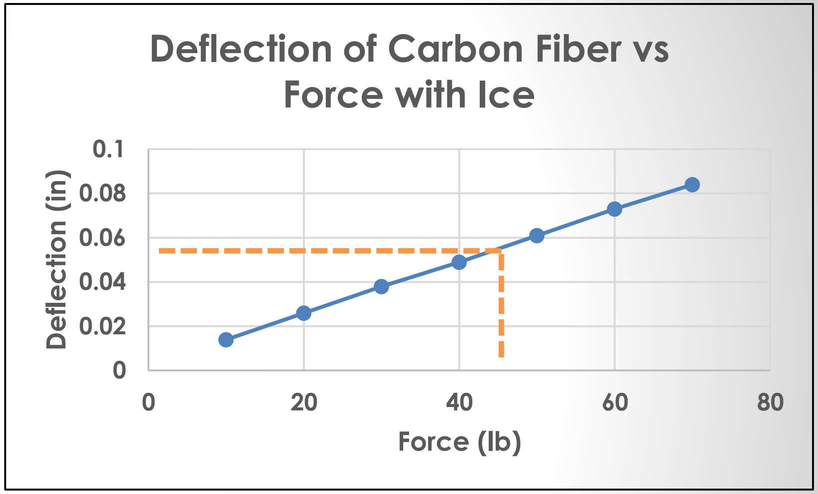
Flat Plate ANSYS Deflection Model



Flat Plate Deflection
Expected Results from ANSYS

Flat Plate Deflection Model





* **Force required to break 3/8 in ice on flat plate = ~45 lb → 0.057 in deflection of carbon fiber w/ ice**

Expected Error in Measurements

Without ice on plate (no ice when measuring in Thorlabs)

Predicted Deflection = 0.230 in ± 0.005 inch

Flat Plate
Wind Cage Test Overview

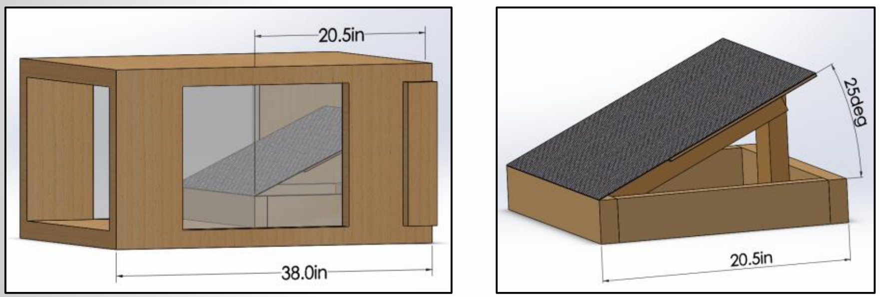
Purpose

- Validate flat plate ANSYS model with force & ice breaking
- Test in representative flight conditions

Requirements Verified

- DR.2.1 The deicing mechanism shall be capable of **removing 3/8 in thick ice** on test section
- SPEC.2.1 The deicing mechanism shall remove ice… with **wind speed = 65 knots**.

Flat Plate Wind Cage Test Setup



Flat plate setup

Leaf blower setup

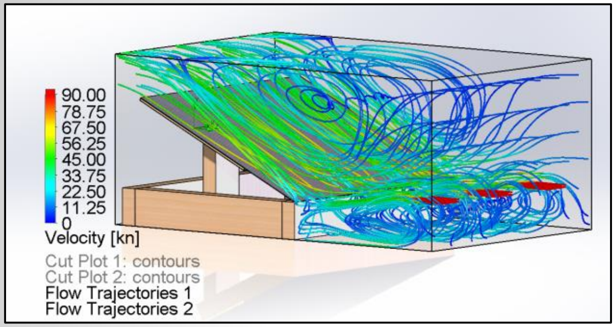
Flat Plate Wind Cage Testing (Complete by: 3/13)

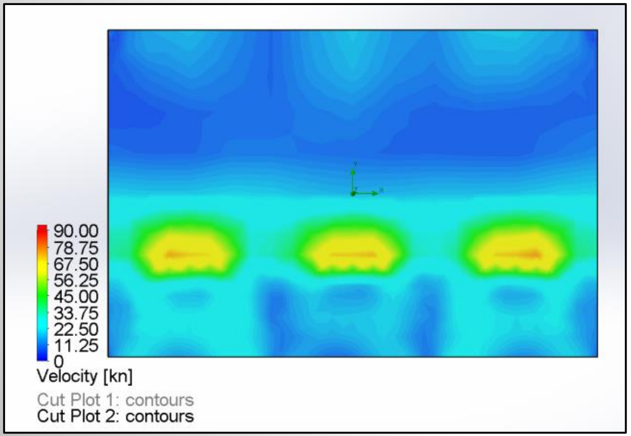
Measure		Calculate
Distance traveled by laser, D(with calipers)	→	Deflection of flat plate (via geometry)

Testing Location: INSTAAR Walk-In Freezer (-11°F)

Flat Plate Wind Cage Expected/Actual Results

3 leaf blowers simulation: each leaf blower located 1 ft from leading edge





CFD Assumptions

- Turbulent and Laminar flow
- Adiabatic Walls
- 1 micro-inch wall roughness

Data from Wind Tunnel Measurements (12 in from outlet)

- At outlets: **68 knots**
- ½ - way between outlets: **7 knots**
- ¼ - way between outlets: **27 knots**

* Distance between outlet centers = 9 in
* Distance between outlet edges = 6 in
* Anemometer diameter = 2.5 in

Full Wing Section Deflection Test Overview

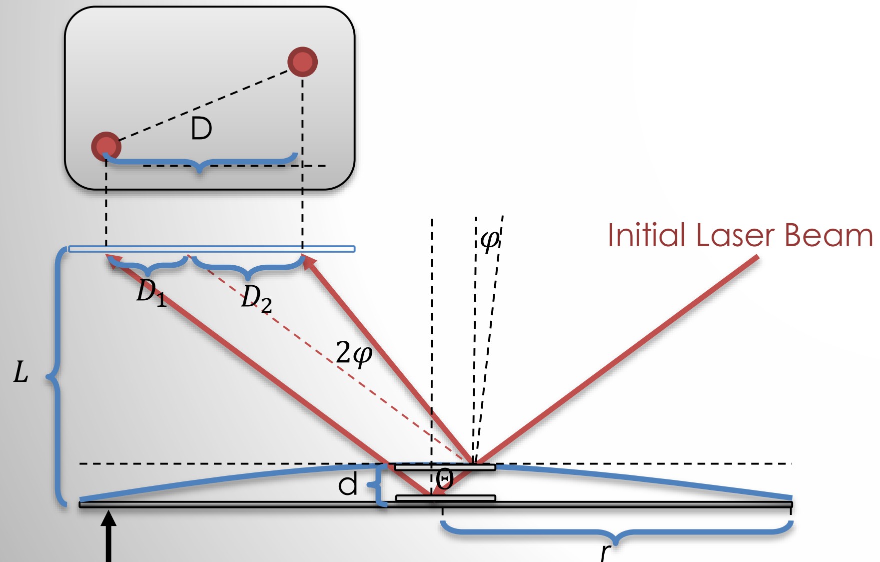
Purpose

- Verify ANSYS deflection model
  - Laser trials complete before level 3 testing

Requirements Verified

- DR.1.3 …deicing mechanism shall **not damage or degrade the structural integrity** of the wing
- DR.2.1 The deicing mechanism shall be capable of **removing 3/8 in thick ice** on test section

Full Wing Section Test Setup



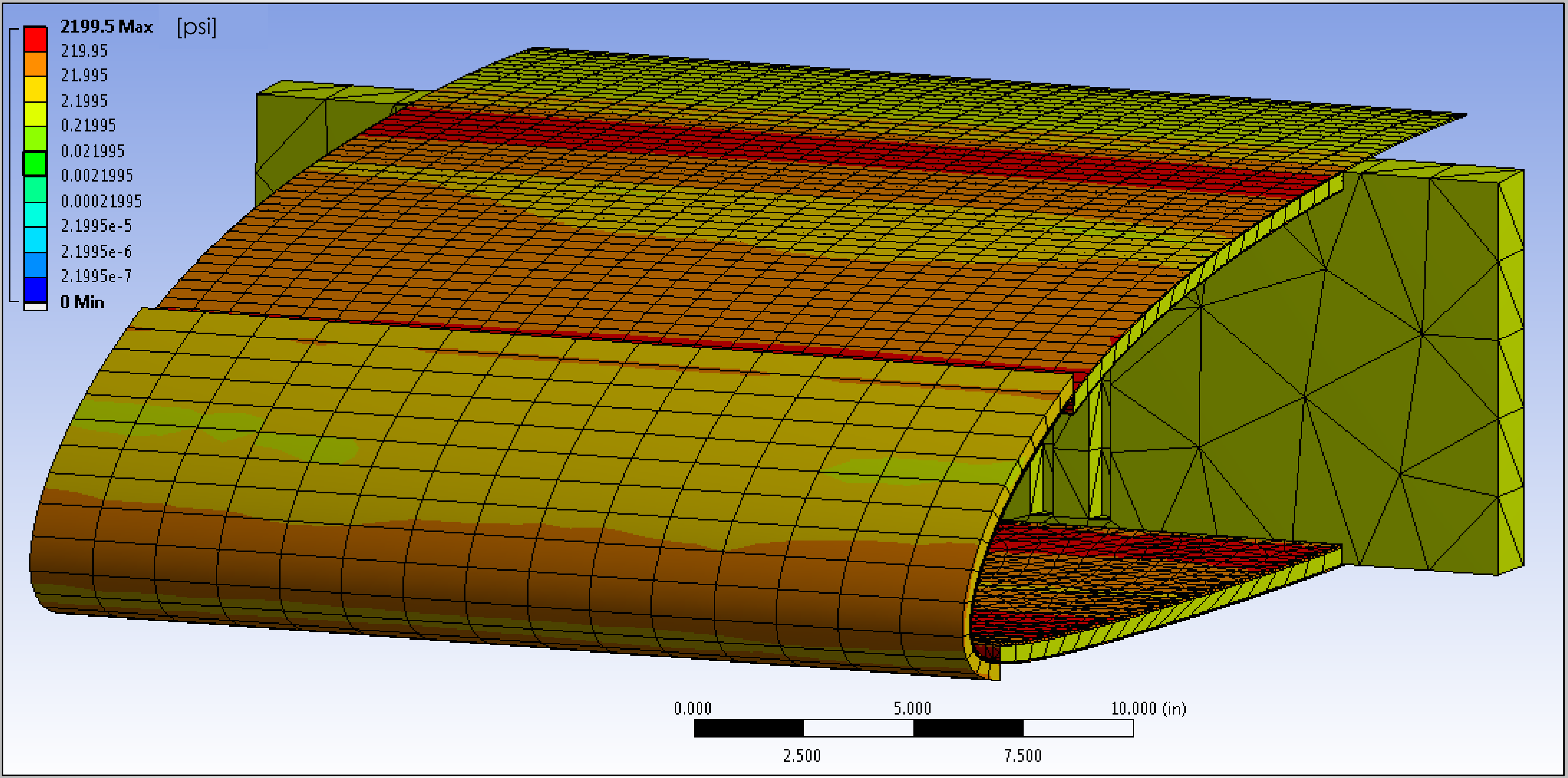
Cross-sectional view of carbon fiber flat plate

Full Wing Section Deflection Testing

Measure		Calculate
Distance traveled by laser, D	→	Deflection of flat plate (via geometry)

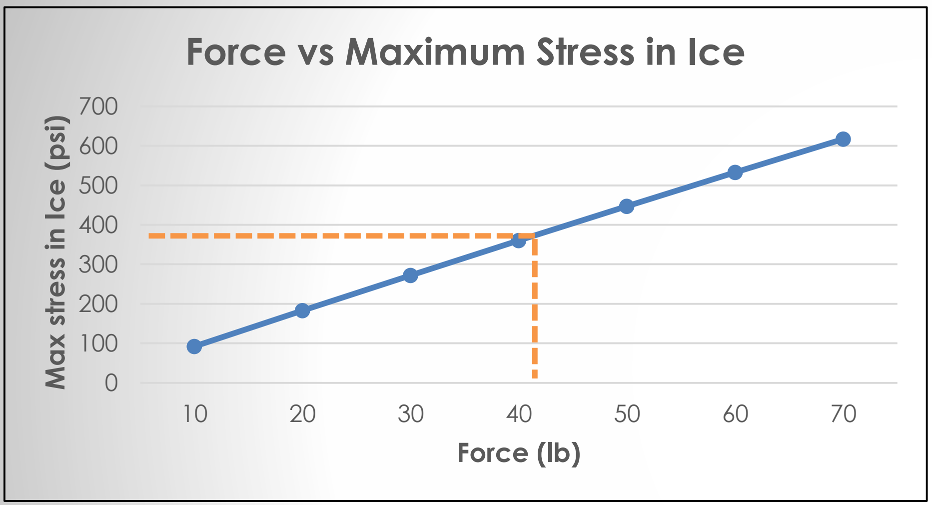
Testing Location: Thorlabs

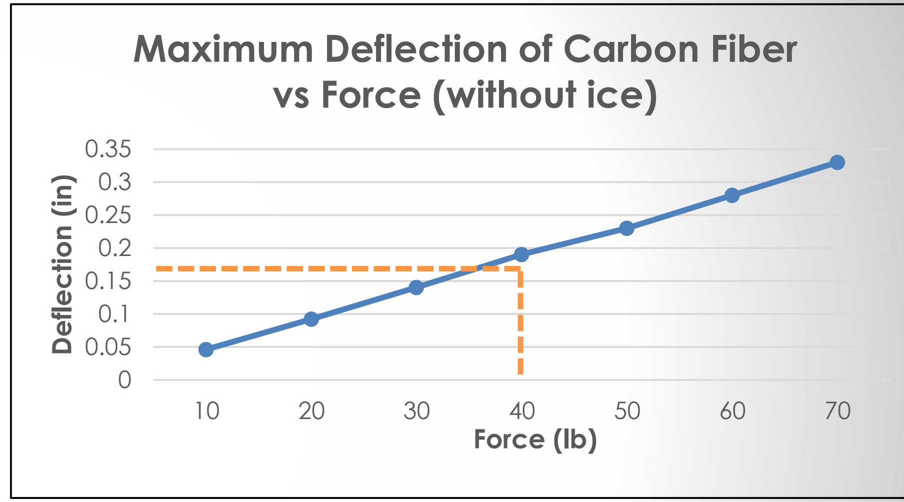
Full Wing Section ANSYS Stress Model



Full Wing Section Deflection ANSYS Expected Results

Full Wing Section Deflection Model





* **Force required to break 3/8 in ice on flat plate = ~40.5 lb → 0.185 in deflection of carbon fiber w/o ice**

Expected Error in Measurements

Without ice on full wing section (when measuring in Thorlabs)
Predicted Deflection = 0.185 in ± deflection error

Full Wing Section Wind Cage Test Overview

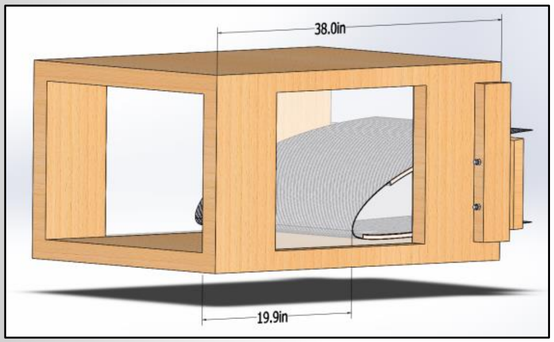
Purpose

- Gather data on ice crack propagation
- Test in representative flight conditions

Requirements Verified

- DR.2.1 The deicing mechanism shall be capable of **removing 3/8 in thick ice** on test section
- SPEC.2.1 The deicing mechanism shall remove ice… with **wind speed = 65 knots**.

Full Wing Section Wind Cage Test Setup



Full Wing Section Setup

Leaf blower setup

Full Wing Section Deflection Testing (Complete by: 4/9)

Measure		Calculate
Distance traveled by laser, D(with calipers)	→	Deflection of flat plate (via geometry)

Test Location: INSTAAR walk-in freezer (-11°F)

Full Wing Section Wind Cage Expected Results

Flat Plate Wind Cage Model

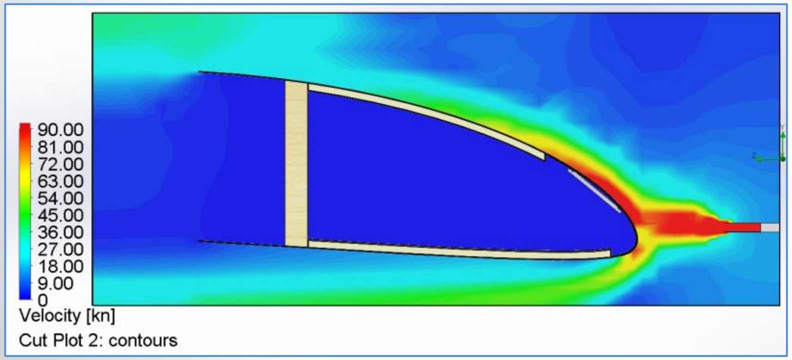
<u>CFD Assumptions</u>

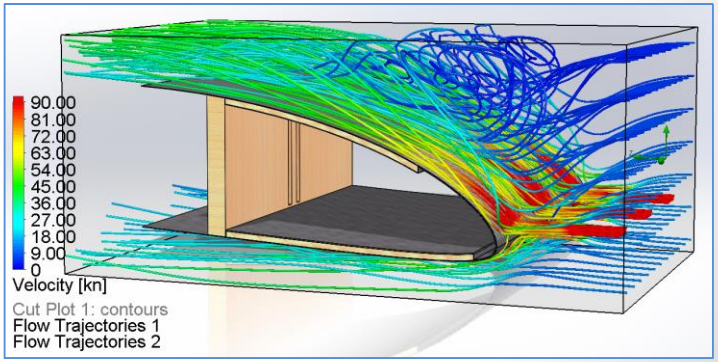
- Turbulent and Laminar flow
- Adiabatic Walls
- 1 micro-inch wall roughness

Data from Wind Tunnel Measurements (12 in from outlet)

- At outlets: **68 knots**
- ½ - way between outlets: **7 knots**
- ¼ - way between outlets: **27 knots**

SolidWorks flow simulation on full wing section (3 leaf blowers)



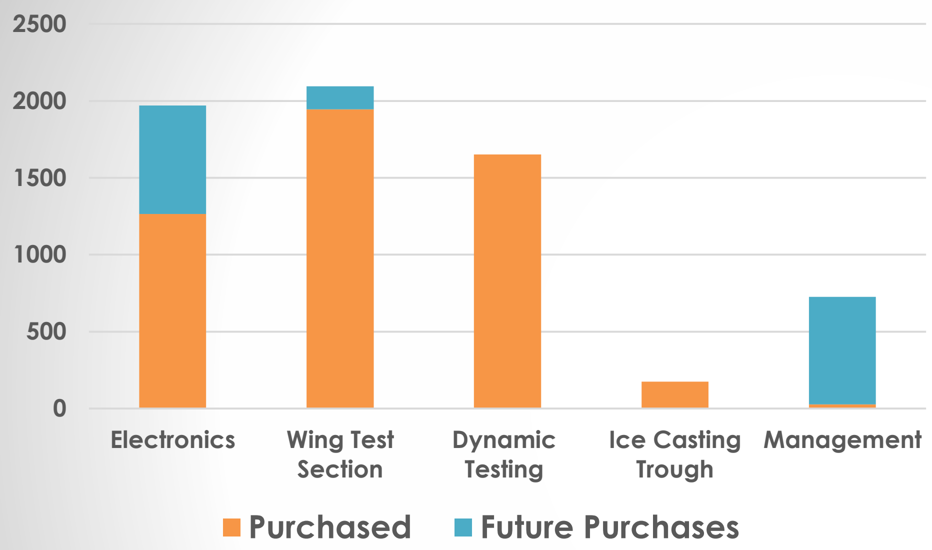


Leaf blower wind speed located 1 ft from leading edge

At leading edge: Avg Speed = 65 knots (up to 85% variation along span)

Budget

Budget Status



<u>Future Expenses</u>:

<u>Electronics:</u>
Capacitors, Micro-Controller, Thyristors, Pillow Bearings

<u>Wing Test Section:</u>
Mold Release, Vacuum Bags, Sealant Tape, Curing Platform

<u>Management:</u>
Symposium Poster, Printing, AIAA Conference

Aerospace Department: **$5,000**	EEF*: **$2,215**	Total Project Cost: **$7,215**

To be Approved

Questions?

Requirements – FR1

FR.1 The full-span system shall be integrable with the Orion UAV.
DR.1.2 The deicing mechanism shall be integrable with a wing in the shape of the DAE11 airfoil.
SPEC.1.2.1 The test section chord length shall be 72 in (6 ft).
DR.1.2.1 The components of the deicing mechanism internal to the wing test section shall fit between the leading edge (0 in.) and half-chord line (36 in.) in the chord-wise direction.
DR.1.3 The installation of the deicing mechanism shall not damage or degrade the structural integrity of the wing.
DR.1.4 The operation of the deicing mechanism shall not damage or degrade the structural integrity of the wing over a lifetime of 150 hours.

Requirements – FR2

FR.2 The deicing mechanism shall remove ice.
SPEC.2.1 The deicing mechanism shall remove ice in an environment with wind speed = 65 knots.
DR.2.1 The deicing mechanism shall be capable of removing 3/8 in thick ice on test section.
SPEC.2.1.1 The ice shall cover the test section from the leading edge to 7% of the chord (7.2 in) as measured chord-wise from the leading edge on the upper airfoil surface and to 2% of the chord (1.7 in) as measured chord-wise from the leading edge on the lower airfoil surface
DR.2.2 The deicing mechanism 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 activating the prototype shall be 0.1 in.

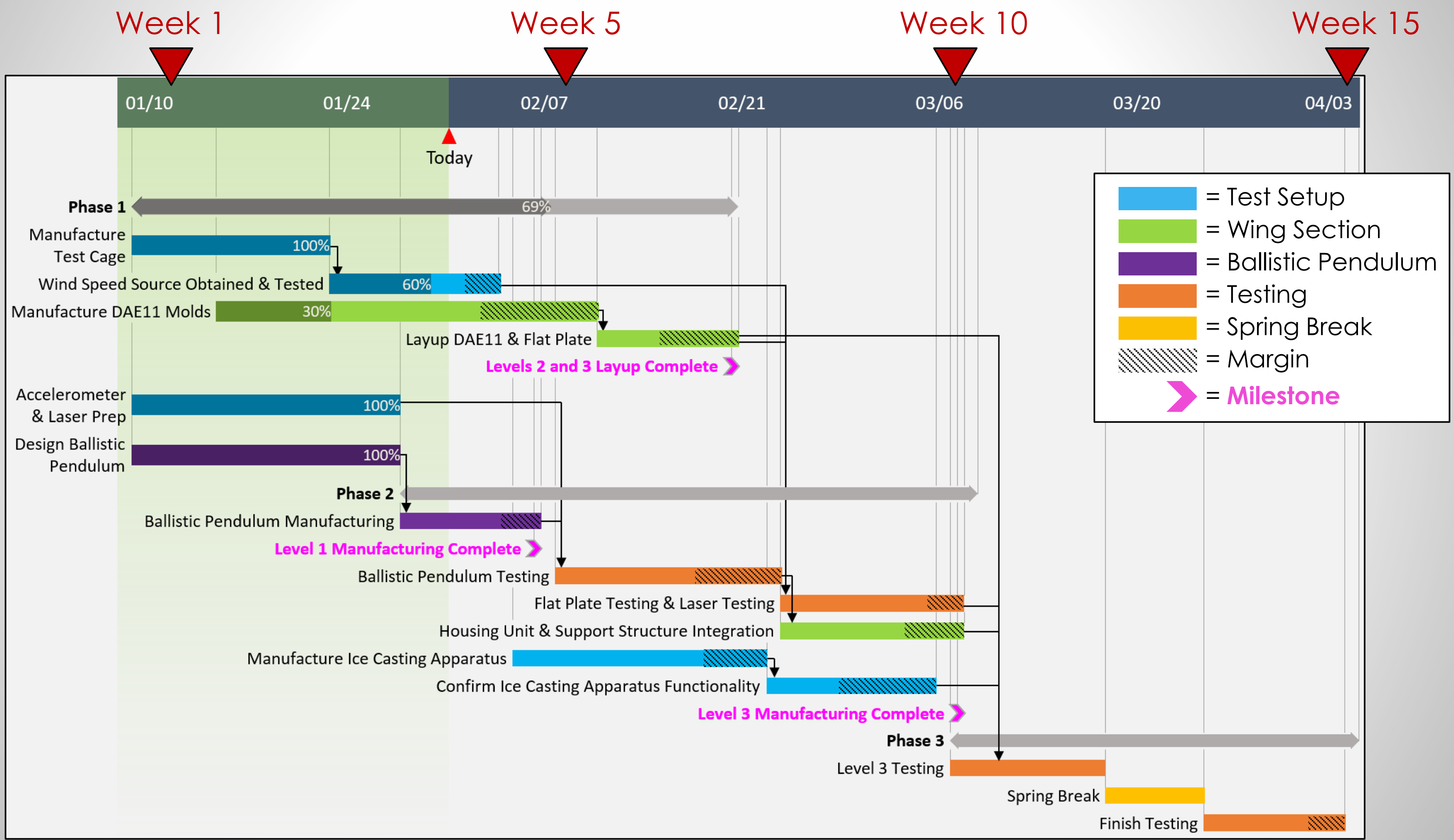
Requirements – FR3

FR.3 The full-span system shall use less than 4kW-hr of energy to deice the wing section.
DR.3.1 The deicing mechanism shall operate on an incoming 28 V DC voltage line.
DR.3.2 The full-span system instantaneous power draw shall be at most 2 kW.

Schedule Backup

Work Plan MSR

Spring 2016



Overview | Schedule | Ballistic Pendulum | Flat Plate Deflection | Flat Plate Wind Cage | Full Wing Deflection | Full Wing Wind Cage | Budget

Ballistic Pendulum Backup

Force Model Verification

Element Size

Calibrate for:

General physics

Predefined: Finer

Custom (selected)

Element Size Parameters

Maximum element size:

16.5 mm

Minimum element size:

1.2 mm

Maximum element growth rate:

1.4

Curvature factor:

0.4

Resolution of narrow regions:

0.7

Element Size

Calibrate for:

General physics

Predefined: Extra fine

Custom (selected)

Element Size Parameters

Maximum element size:

10.5 mm

Minimum element size:

0.85 mm

Maximum element growth rate:

1.35

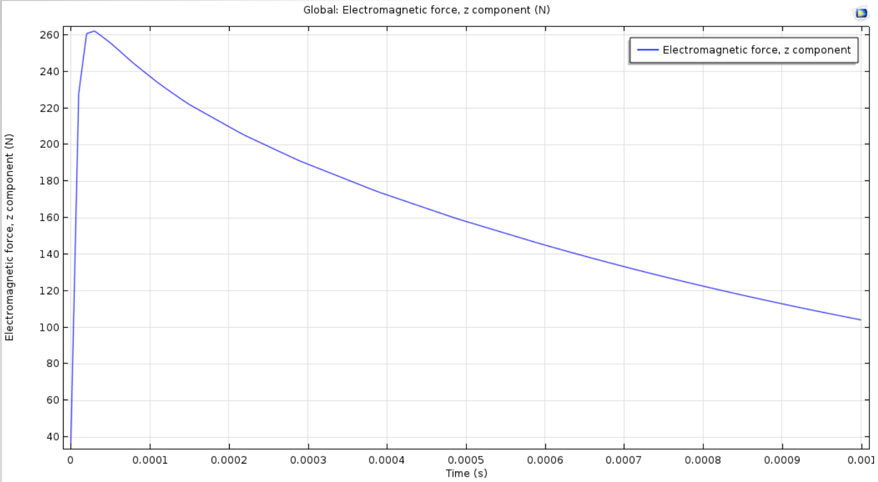
Curvature factor:

0.3

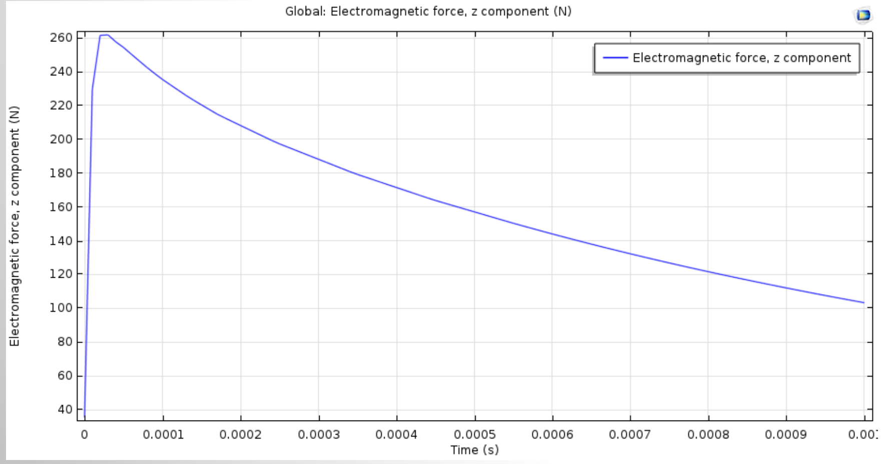
Resolution of narrow regions:

0.85

Force Model Verification



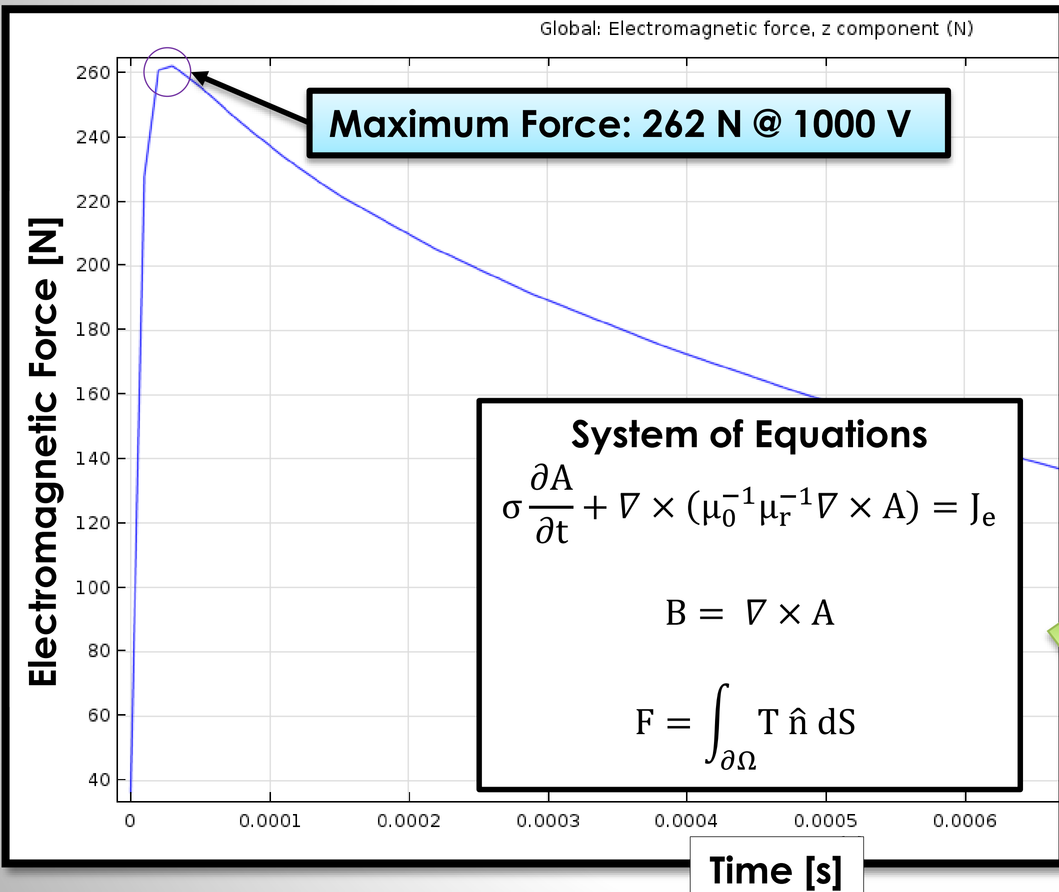
Finer



Extra Fine

Recall: Solenoid Force Model Derivation BACKUP

Goal: Determine *max* impulsive force from **solenoid** using COMSOL model

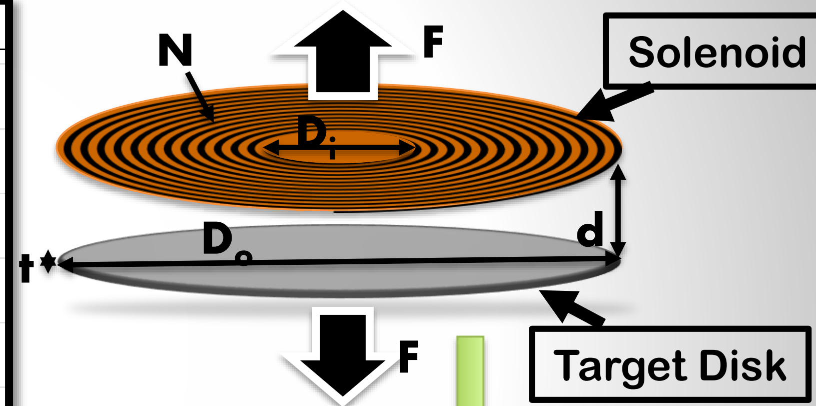


System of Equations

$$\sigma \frac{\partial A}{\partial t} + \nabla \times (\mu_0^{-1}\mu_r^{-1}\nabla \times A) = J_e$$

$$B = \nabla \times A$$

$$F = \int_{\partial\Omega} T\,\hat{n}\,dS$$

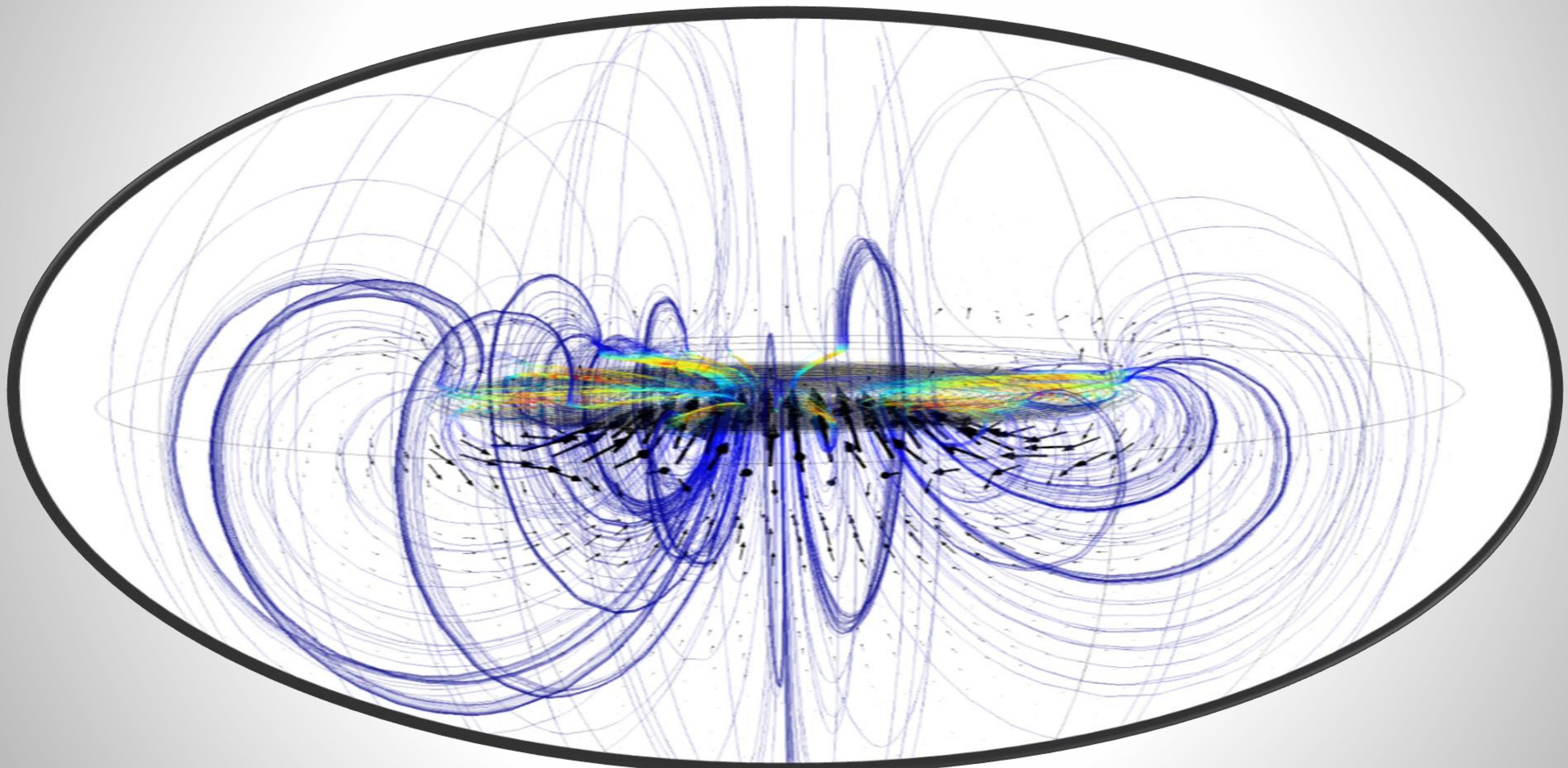


Input Parameters

- I – Current
- N – Number of wire loops
- H – Height
- D – Diameters
- d – Gap distance
- σ – Electric conductivity
- μ – Magnetic permeability

COMSOL Model Backup

Magnetic field lines from COMSOL model

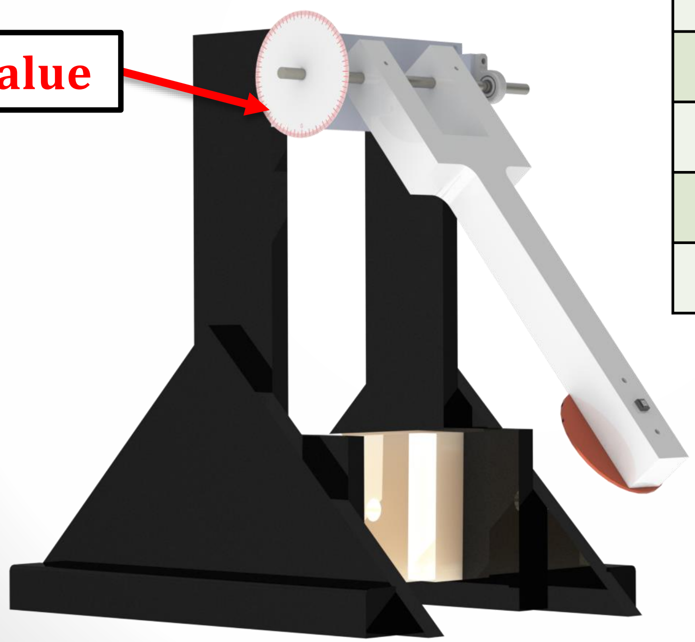


Ballistic Pendulum
Energy Conservation Method

Goal: Determine impulsive force from **energy conservation**

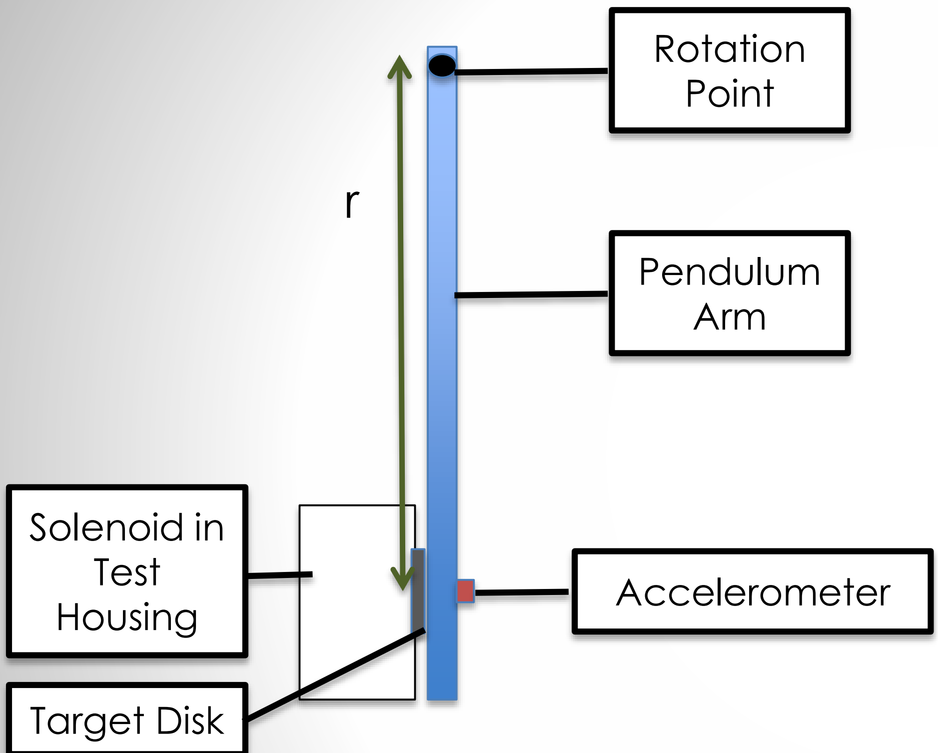
$$F = ma = m\frac{v}{\Delta t} = \frac{m\sqrt{6gL_{cm}(1-\cos\theta)}}{\left(\frac{I}{R}\right)\ln\left(\frac{V}{V_0}\right)}$$

θ – Measured Value



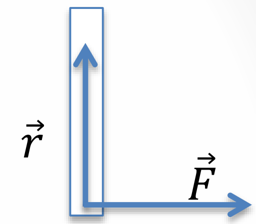
Constants	Variable
Mass	m
Gravity	g
Discharged Voltage	V
Initial Voltage	V_o
Resistance	R
Inductance	I

Accelerometer Backup



Use torque:

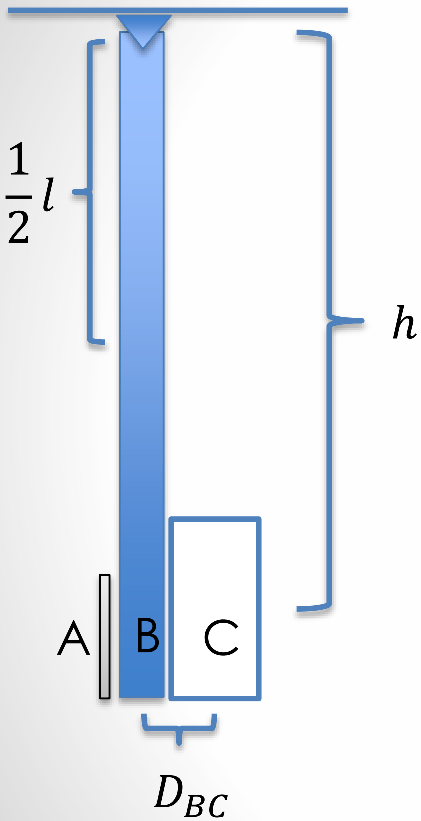
$$\tau = r * F * sin\theta = I * \alpha$$



$$F = \frac{I * \alpha}{r} = \frac{I * a_{tan}}{r^2}$$

Assume:
- Max force applied at first instant
- Force applied exactly perpendicular to pendulum arm
- I (full pendulum arm) ≈ I (pendulum arm from top to accelerometer)
- Negligible friction in bearings

Acceleration: Impact Model

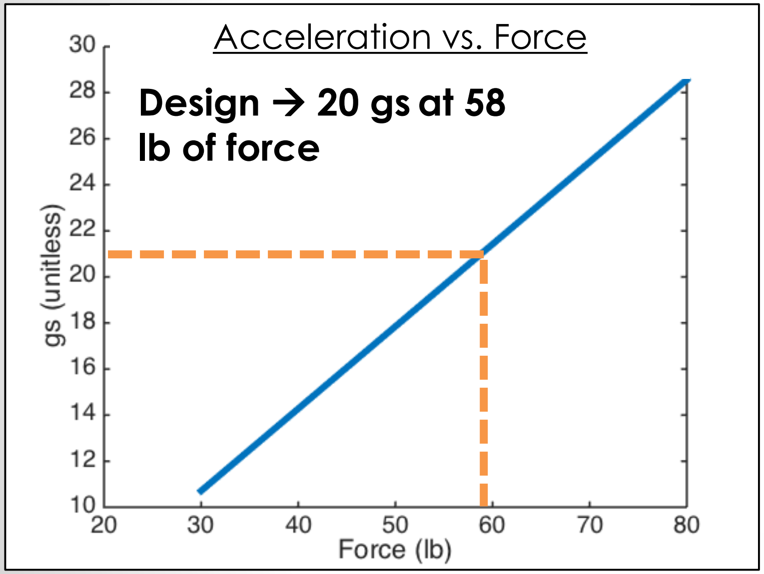


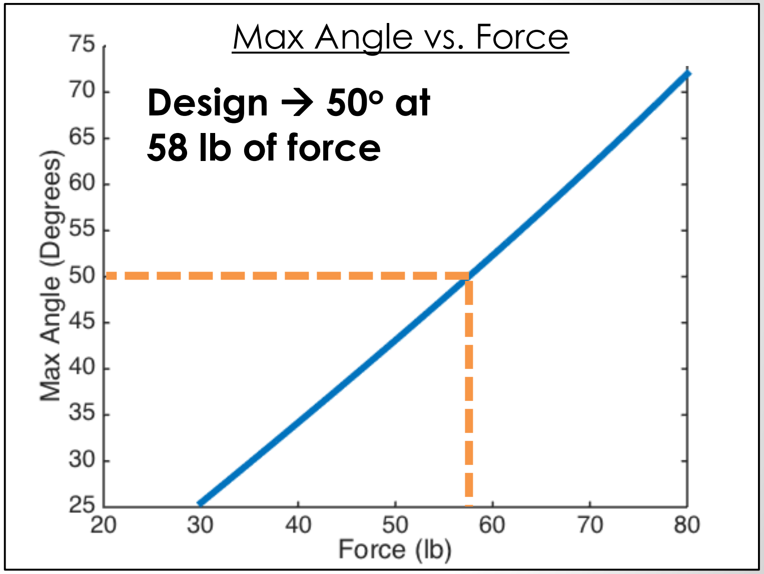
$$\begin{cases} H'_A = h m_A V'_A + I_A \omega'_A \\ H'_B = \frac{1}{2} l m_B V'_B + I_B \omega'_B \\ H'_C = h m_C V'_C + I_C \omega'_C \\ \omega'_A = \omega'_B = \omega'_c \end{cases}$$

$$F = \frac{\int_{t_1}^{t_2} a\,dt}{\Delta t h}\left[h m_C \sqrt{{D_{BC}}^2 + h^2} + \frac{1}{4} l^2 m_B + (I_B + I_c) \right]$$

Solenoid Force Model & Predicted Results

Acceleration & Max Angle Models



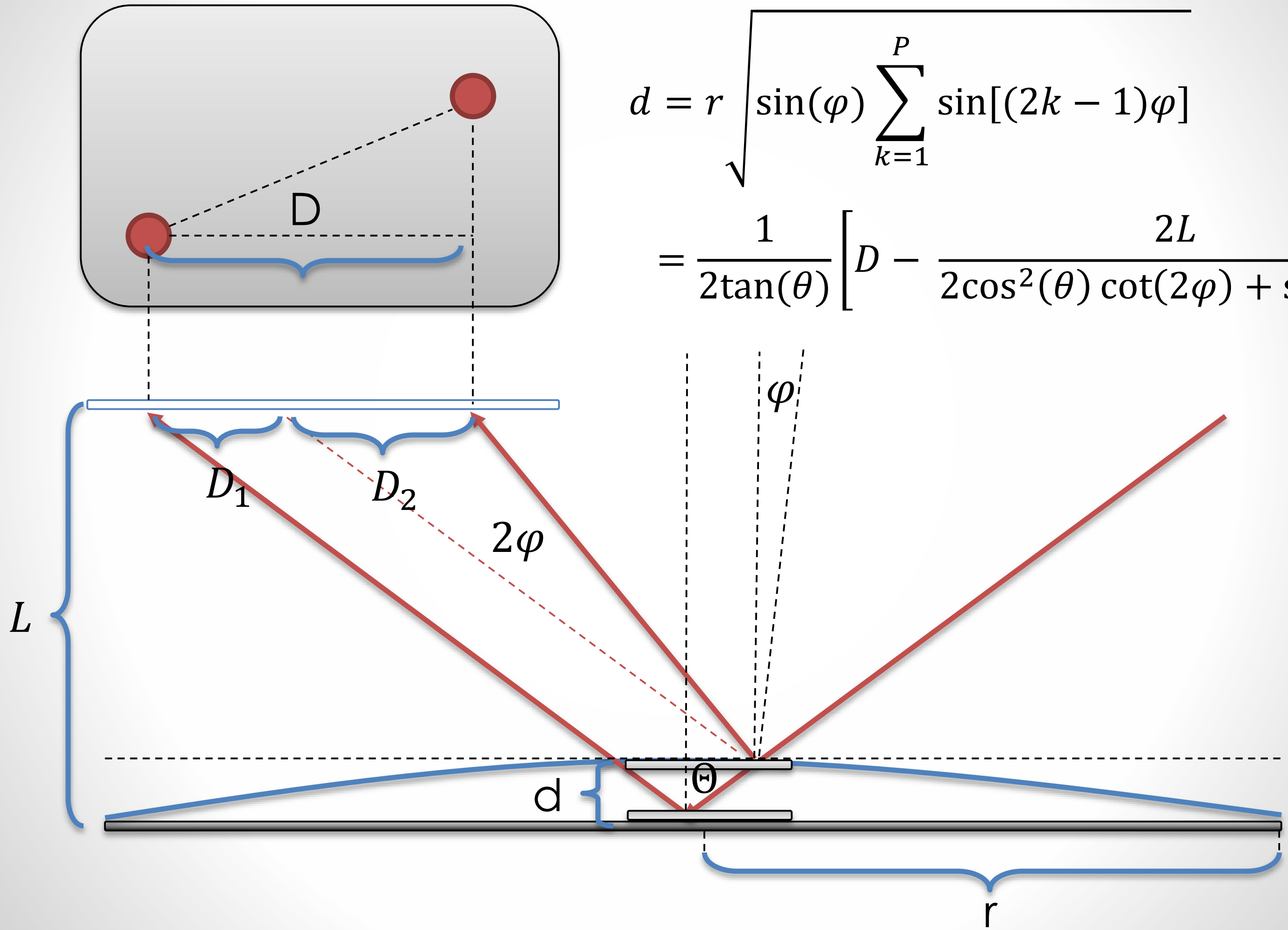


Deflection Backup

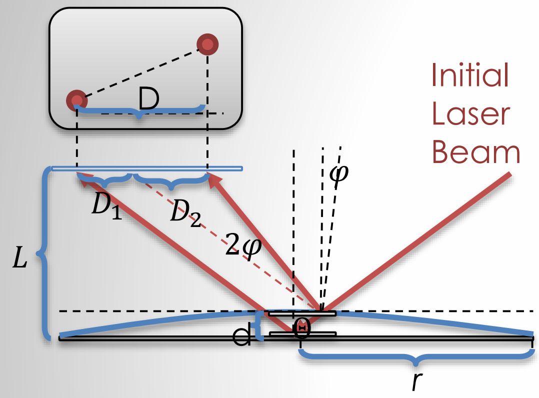
Deflection Measurement

$$d = r\sqrt{\sin(\varphi)\sum_{k=1}^{P}\sin[(2k-1)\varphi]}$$

$$= \frac{1}{2\tan(\theta)}\left[D - \frac{2L}{2\cos^2(\theta)\cot(2\varphi) + \sin(2\theta)}\right]$$



Deflection Uncertainty



$$d = \frac{1}{2\tan\theta}\left[D - \frac{2L}{2\cos^2\theta\cot(2\varphi) + \sin(2\theta)}\right]$$

$$\delta d = \sqrt{\left(\frac{\partial d}{\partial D}\delta D\right)^2 + \left(\frac{\partial d}{\partial \theta}\delta \theta\right)^2 + \left(\frac{\partial d}{\partial L}\delta L\right)^2}$$

$$\frac{\partial d}{\partial D} = \frac{1}{2\tan\theta}$$

$$\frac{\partial d}{\partial L} = -\frac{1}{\tan\theta\left[2\cos^2\theta\cot(2\varphi) + \sin(2\theta)\right]}$$

$$d = 2D\tan^{-1}\theta + \left(-2L\tan^{-1}\left[2\cos^2\theta\cot(2\varphi) + \sin(2\theta)\right]^{-1}\right)$$

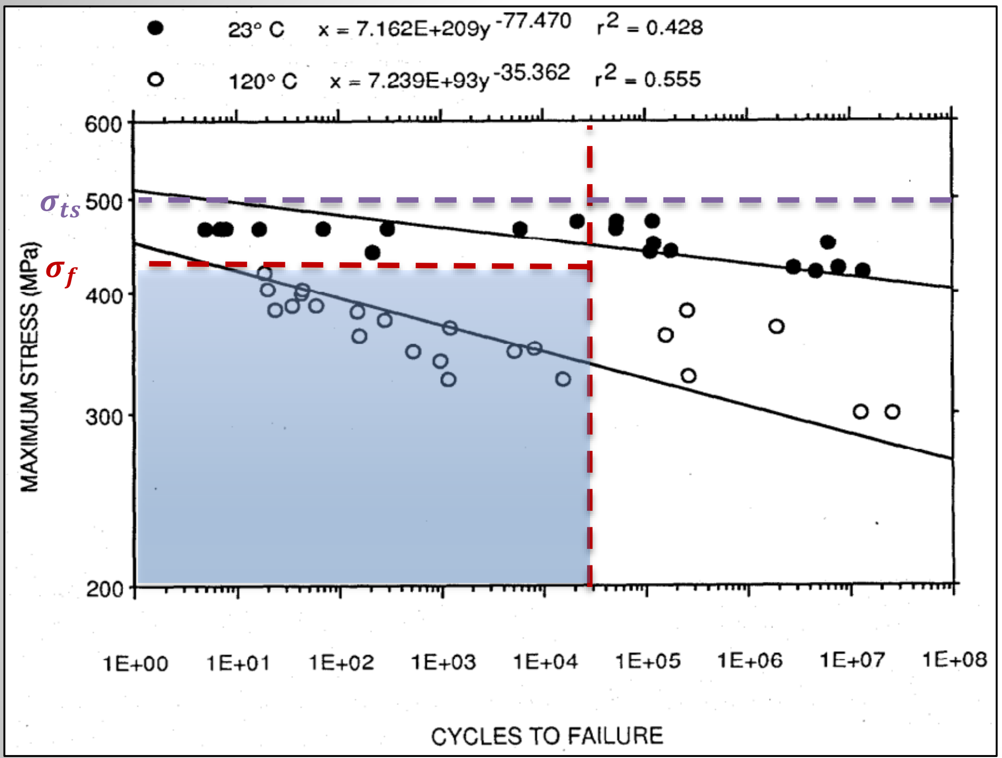
$$\frac{\partial d}{\partial \theta} = 2D(-1)\tan^{-2}\theta \cdot \sec^2\theta + \Big\{-2L(-1)\tan^{-2}\theta\sec^2\theta\left[2\cos^2\theta\cot(2\varphi) + \sin(2\theta)\right]^{-1}$$

$$-2L\tan^{-1}\theta\,(-1)\left[2\cos^2\theta\cot(2\varphi) + \sin(2\theta)\right]^{-2}\cdot\left[4\cos\theta\cdot(-\sin\theta) + 2\cos(2\theta)\right]\Big\}$$

$$= -2D\frac{\sec^2\theta}{\tan^2\theta} + \frac{2L\sec^2\theta}{\tan^2\theta\left[2\cos^2\theta\cot(2\varphi) + \sin(2\theta)\right]} + \frac{2L}{\tan\theta}\frac{\left[2\cos(2\theta) - 2\sin(2\theta)\right]}{\left[2\cos^2\theta\cot(2\varphi) + \sin(2\theta)\right]}$$

$$= -2D\csc^2\theta + \frac{2L\csc^2\theta}{2\cos^2\theta\cot(2\varphi) + \sin(2\theta)} + \frac{4L\left(\cos 2\theta - \sin 2\theta\right)}{\tan\theta\left[2\cos^2\theta\cot(2\varphi) + \sin(2\theta)\right]^2}$$

Fatigue



Lifetime requirement: $150\ h \left(\frac{60\ min}{1\ h}\right)\left(\frac{3\ pulses}{1\ min}\right) = \mathbf{2.7x10^4\ cycles}$

$$\sigma_{max} = 207\ MPa$$

Stress in wing under normal flying conditions:

$$\epsilon = 1500\ \mu$$

$$\sigma_{min} = E\epsilon = (41\ GPa)(1500\ \mu) = 61\ \text{MPa}$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} = 45.5\ MPa$$

Goodman's Relation:

$$\sigma_a = \sigma_f\left(1 - \frac{\sigma_m}{\sigma_{ts}}\right) = 425MPa\left(1 - \frac{45.5\ MPa}{500MPa}\right)$$

$$\sigma_{a,max} = \mathbf{386\ MPa}$$

Maximum allowable stress amplitude

$$\sigma_{a,actual} = \frac{\sigma_{max} - \sigma_{min}}{2} = \mathbf{73\ MPa}$$

✓ Actual stress amplitude is less than maximum

Full Span Analysis Backup

Power Consumption

$$Total\ Energy = \#\ of\ Solenoids\ * \#\ of\ Impulses * \frac{Energy}{Impulse}$$

$$Total\ Energy = 76\ Solenoids\ * 3\ Impulses * 500\ \frac{Joules}{Impulse}$$

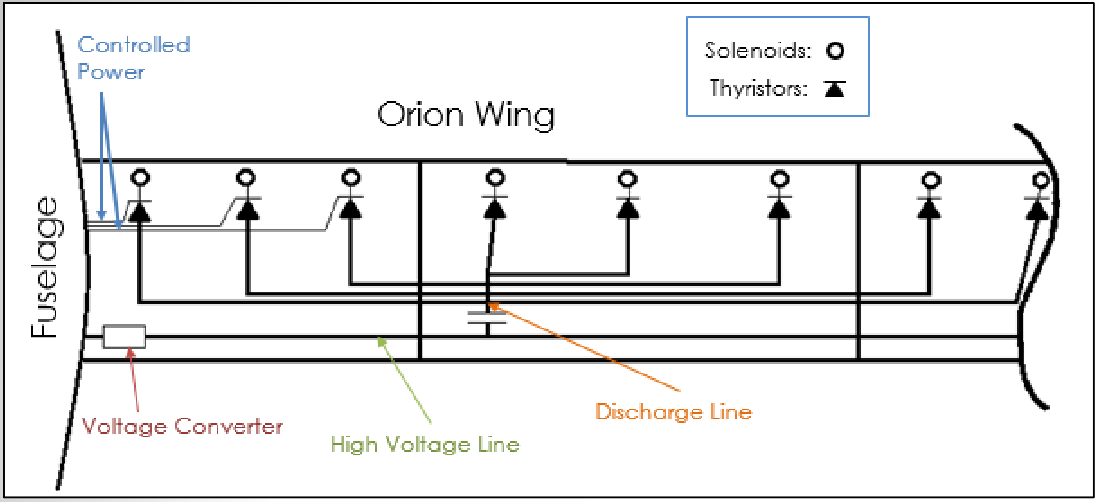
Total Energy = 114,000 Joules

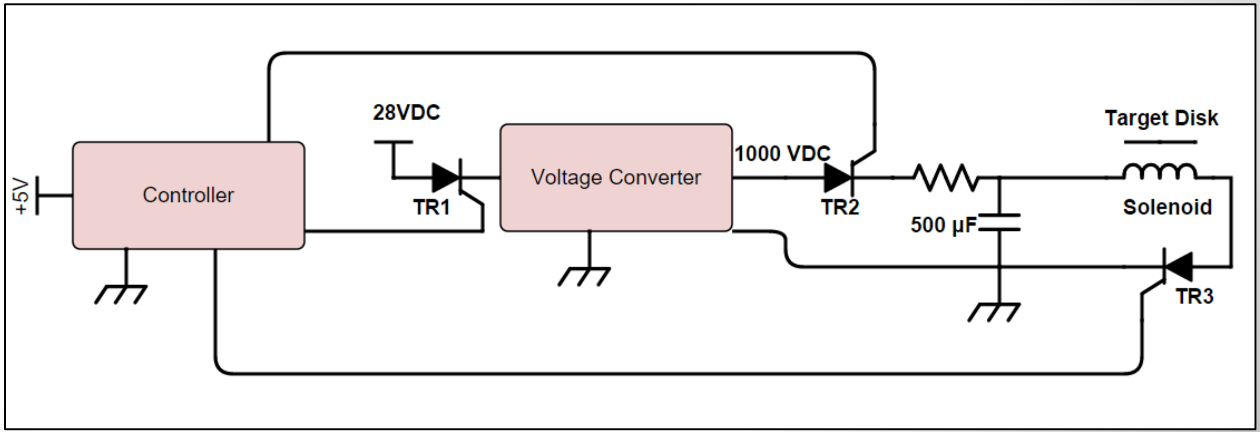
↓

Power = 2 kW for 1 min or 100 W for 17 min

✓ **Power required to run mechanism will not exceed 2kW**

Full-span Backup





Overview | Schedule | Ballistic Pendulum | Flat Plate Deflection | Flat Plate Wind Cage | **Full Wing Deflection** | Full Wing Wind Cage | Budget

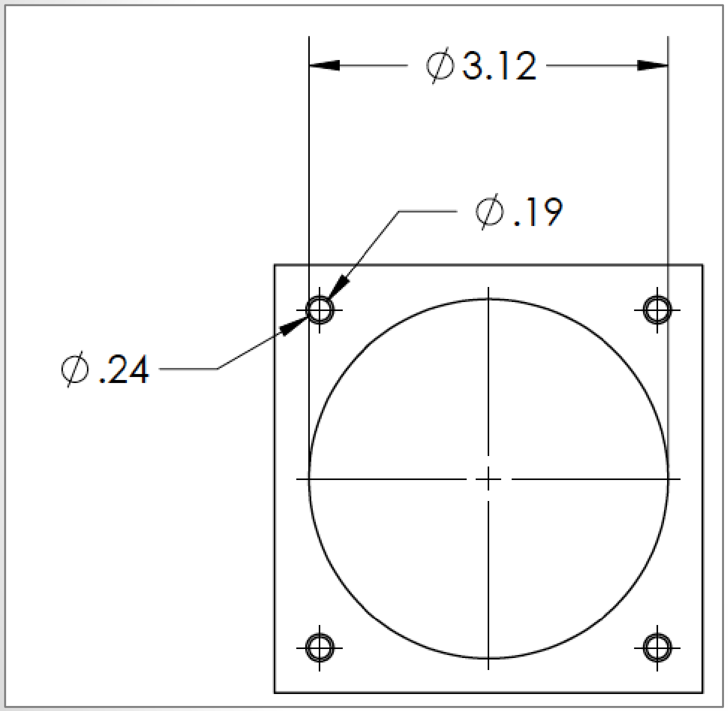
Full-span Weight Budget

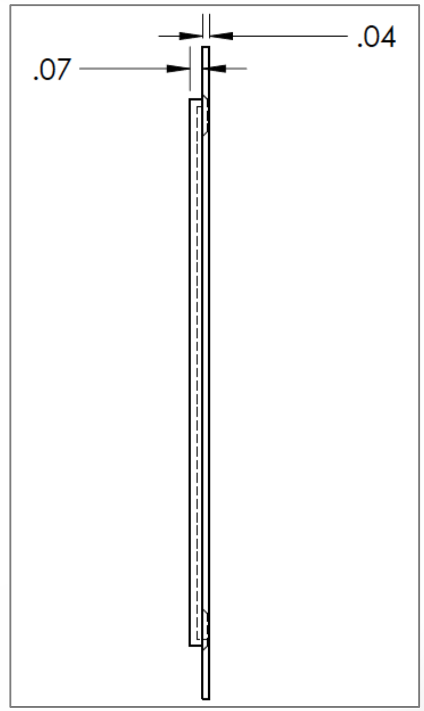
Item	Weight (lb)
Solenoids + Target Plates (76)	38.3
Housings (76)	69.3
Capacitors + Mounting (10)	27.2
Wire + Mounting	30.7
Voltage Converters	55.0
Total	221 lb

Manufacturing Backup

Wing Section Backup – Housing Unit

Housing Unit SolidWorks Designs



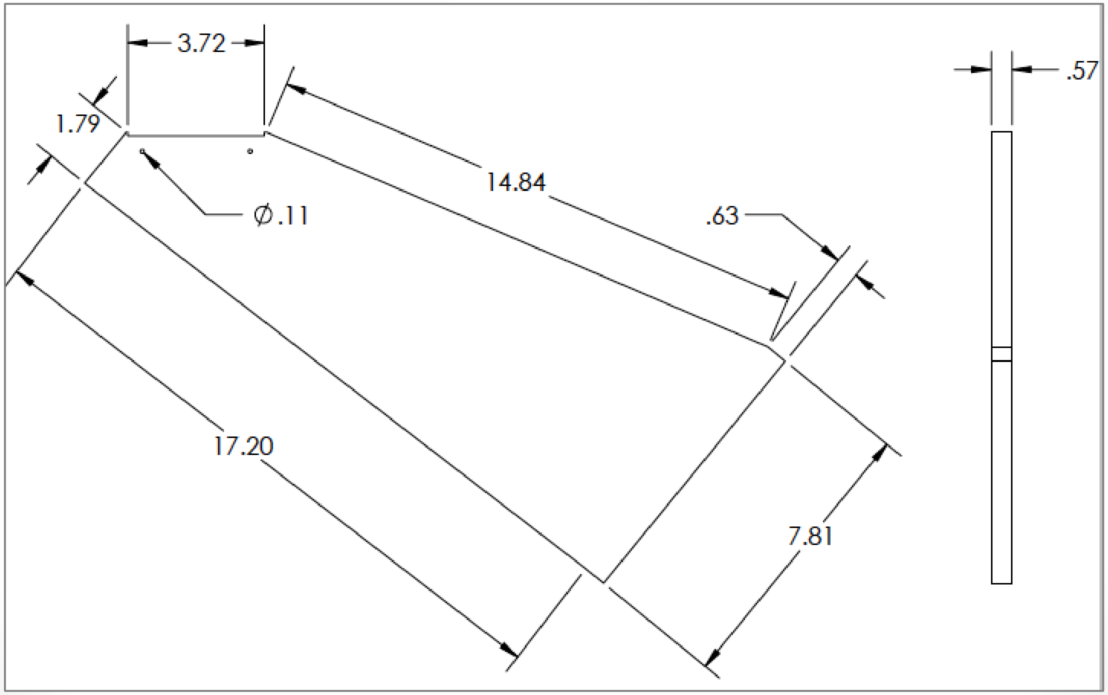


* All units in inches

Tolerance = 0.01 inches

Wing Section Backup – Support Structure

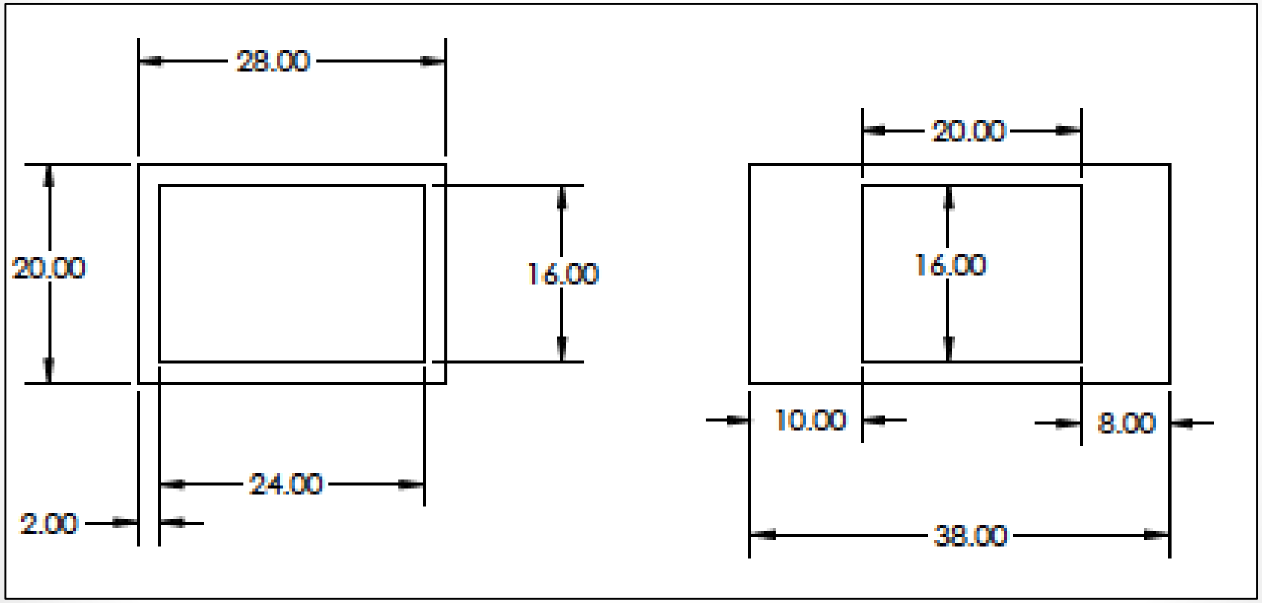
Support Structure SolidWorks Designs



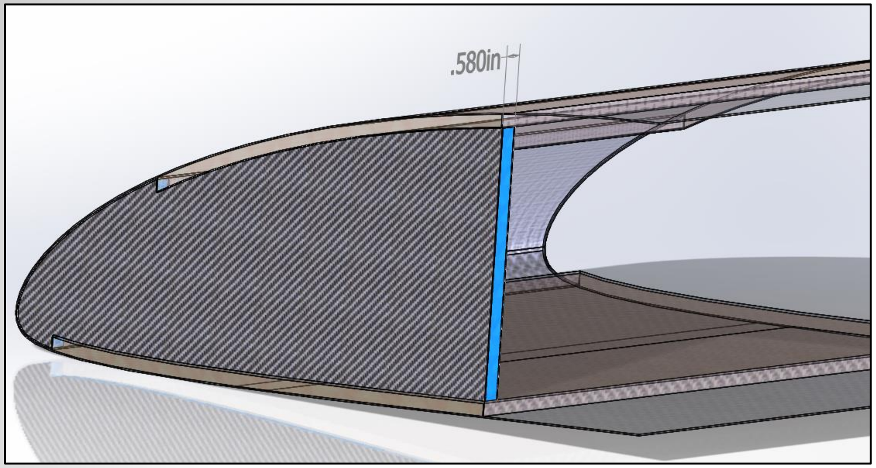
* All units in inches   Tolerance = 0.01 inches

Test Cage Backup

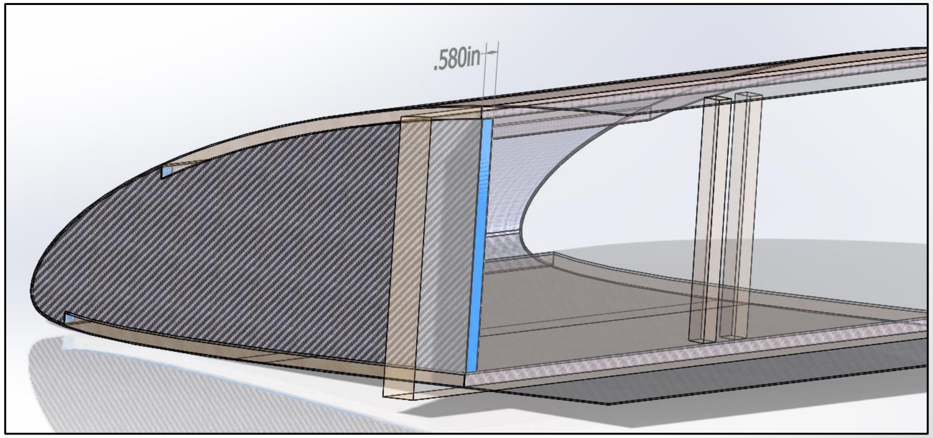
Test Cage (all units in inches)



Wing Section Rib Backup



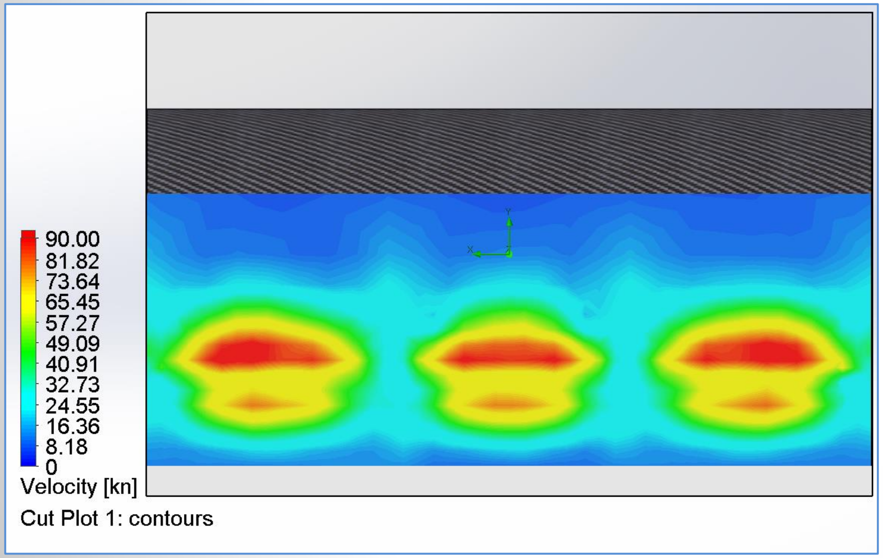
Dragon Plate Rib
(Carbon Fiber plates with foam core)

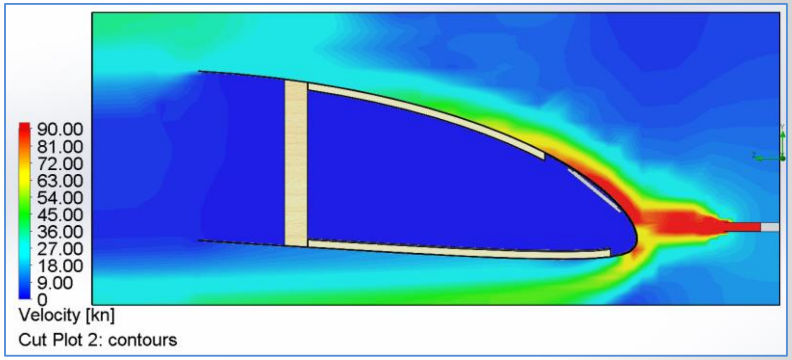


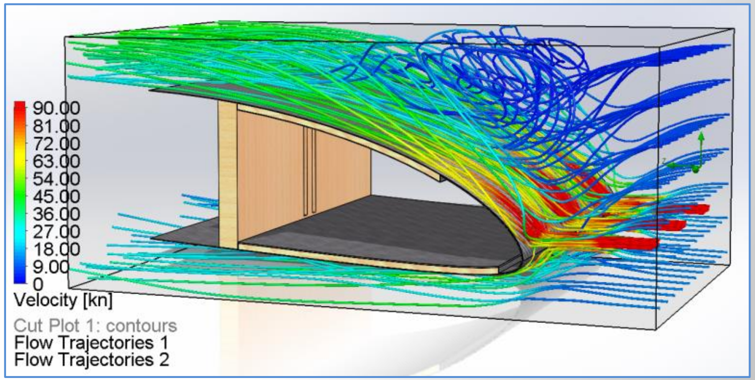
Test Setup Backup

Test Setup Backup

Leaf Blower Simulation
→ 3 Leaf blowers simulated in test cage with exit velocity = 250 knots







Flow Simulation Details

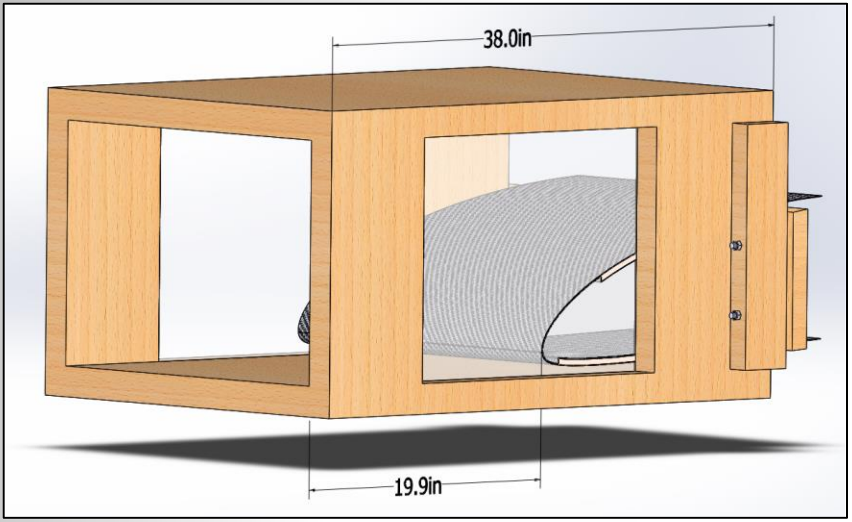
Flow Sim Boundary Conditions:-at leaf blower outlets: **250 knots**
-at test cage inlet/outlet: environmental pressure (**12.2 psi**)

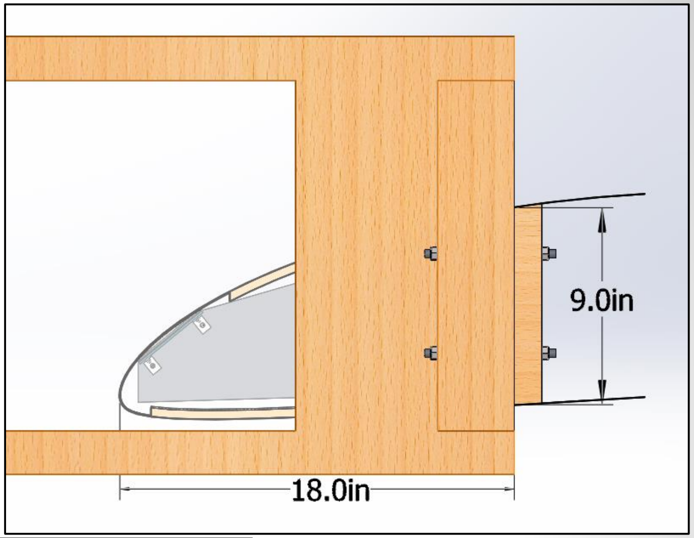
Flow Sim Initial Conditions:
-Environmental pressure (**12.2 psi**)
-Environmental Temp: **-11 F**
-Turbulence intensity: **2%**
-Turbulence length: **0.2 in**
-Velocity: **0 kn**

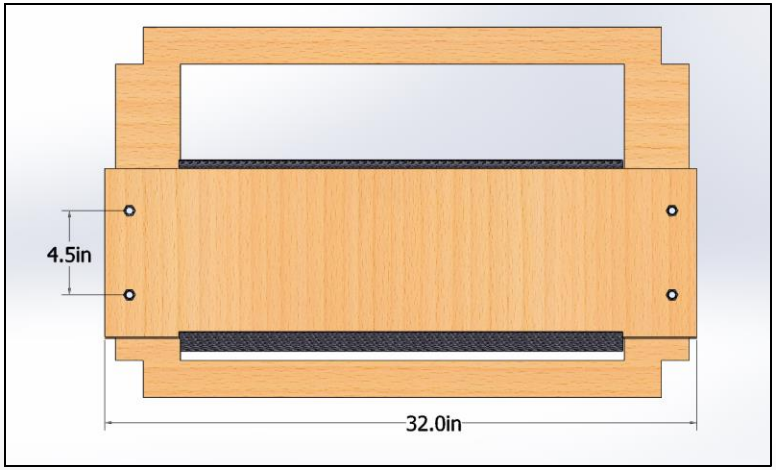
Flow Sim Misc Parameters:
-Turbulent and Laminar flow
-Adiabatic Walls
-**1 microinch** wall roughness

Wind Tunnel Measurements (12 in from outlet):
-at outlets: **68 knots**
-halfway between outlets: **7 knots**
-quarter way between outlets: **27 knots**
(distance between outlet centers was 9 in;
distance between outlet edges was 6 in; anemometer diameter is 2.5 in)

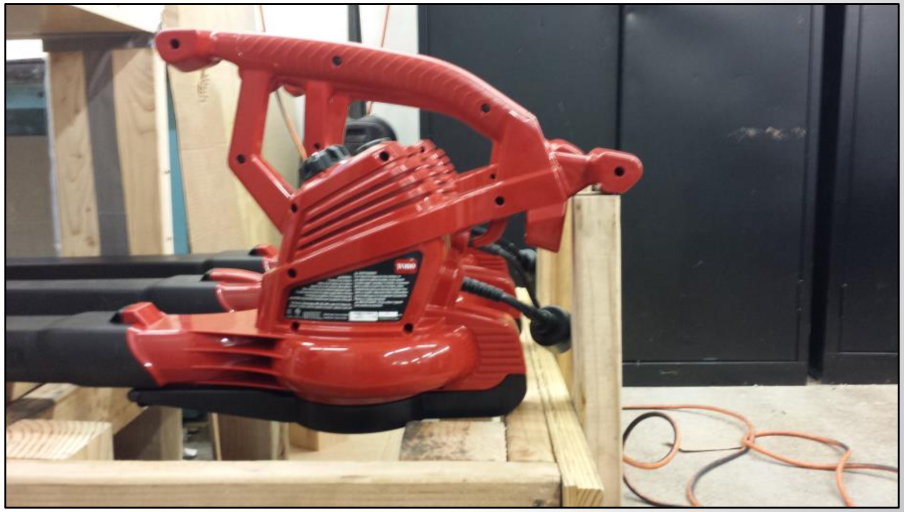
Wing Section Wind Cage Backup







Leaf Blower Stand



Budget Breakdown

Electrical Purchases	
Ribbon Wire	$400
Diode damper, Capacitors, Resistors, Switch	$525
Nylon for Pendulum Arm	$147
Total:	$1,072

Ice Casting Apparatus	
Low Density Poly	$15
Acrylic	$90
Aluminum Blocks	$63
Total:	$168

Budget Breakdown

Wing Test Section	
High Density Foam	$1,530
Vacuum Bag Roll	$78
Peel Ply Roll	$43
Quick Lock Seals / Tape	$100
Mold Release	$17
Dragon Plate	$599
Nomex Honeycomb	$217
Total:	$2,584

Budget Breakdown

Dynamic Testing	
Fan	$706
Leaf Blowers	$150
Wood / Home Depot	$120
Total:	$976