AESIR

University of Colorado at Boulder

Actuated Electromagnetic System for Ice Removal

Critical Design Review
December 1, 2015

Customers

Ellis Langford, Ed Wen

Advisor

Joe Tanner

Kelly Allred | Jacquie Godina | Andrew Moorman
Jonathan Eble | Andre Litinsky | Libby Thomas
Nicole Ela | Runnan Lou | Colin Zohoori

Agenda

- Project Description
- Design Solution
- Verification & Validation
- Project Planning

Project Description

Project Description | Design Solution | Verification & Validation | Planning

Problem Statement

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

- High Endurance
- Low Power Consumption

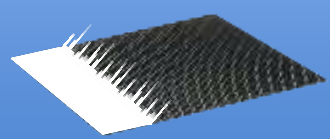
Orion UAV[1]

Project Description | Design Solution | Verification & Validation | Planning

Levels of Success

Level 1

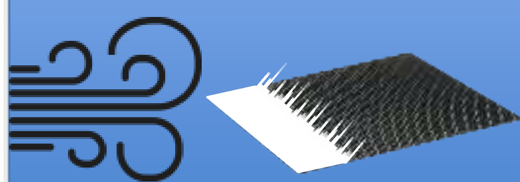
Carbon fiber **flat plate** test section + **de-icing mechanism** + **cast ice**



Baseline

Level 2

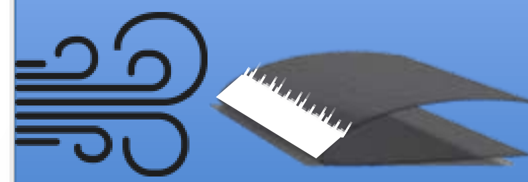
Carbon fiber **flat plate** test section + **de-icing mechanism** + **cast ice** + **wind speed**



+ Wind

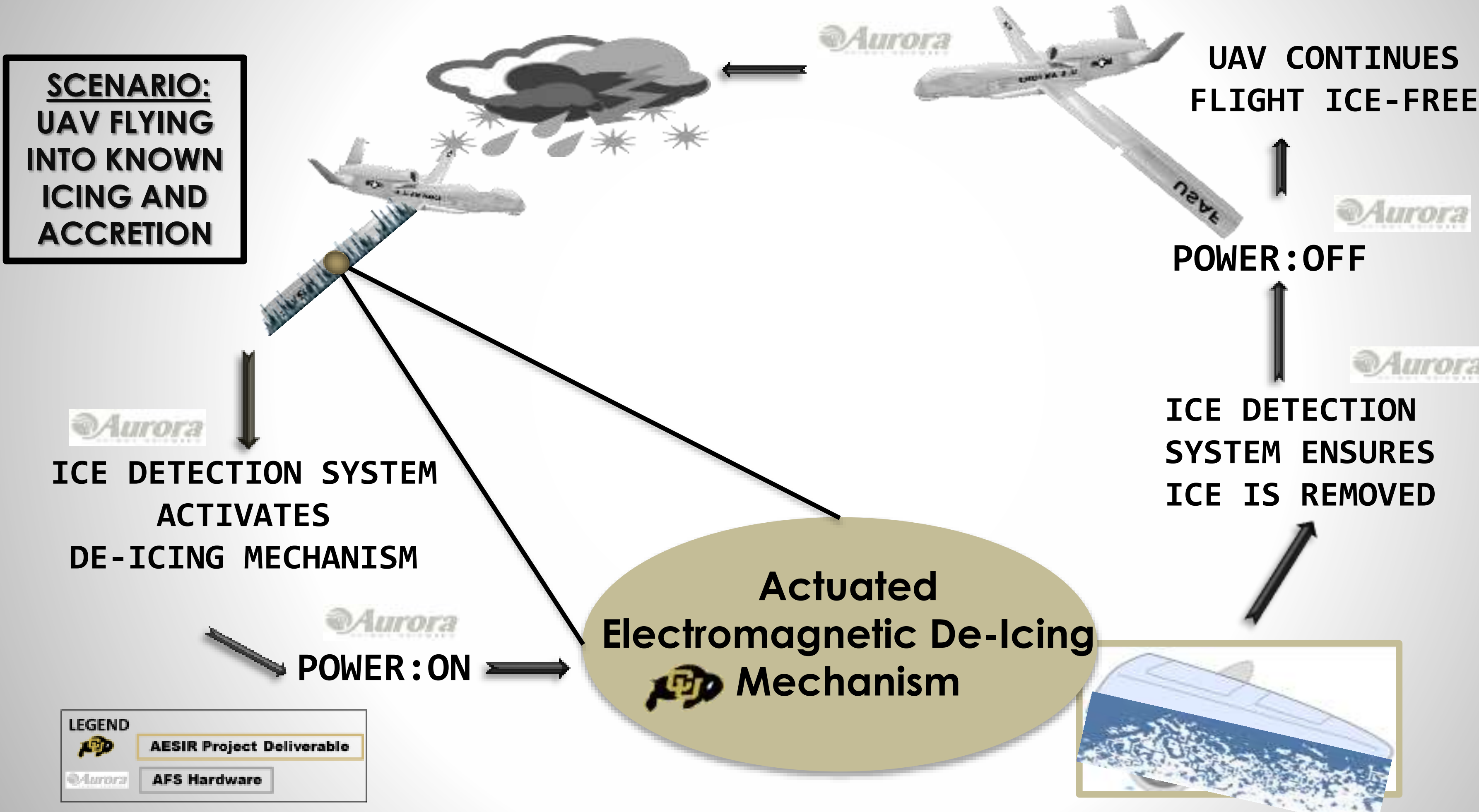
Level 3

Carbon fiber **DAE11** test section + **de-icing mechanism** + **cast ice** + **wind speed**



+ Airfoil Curvature

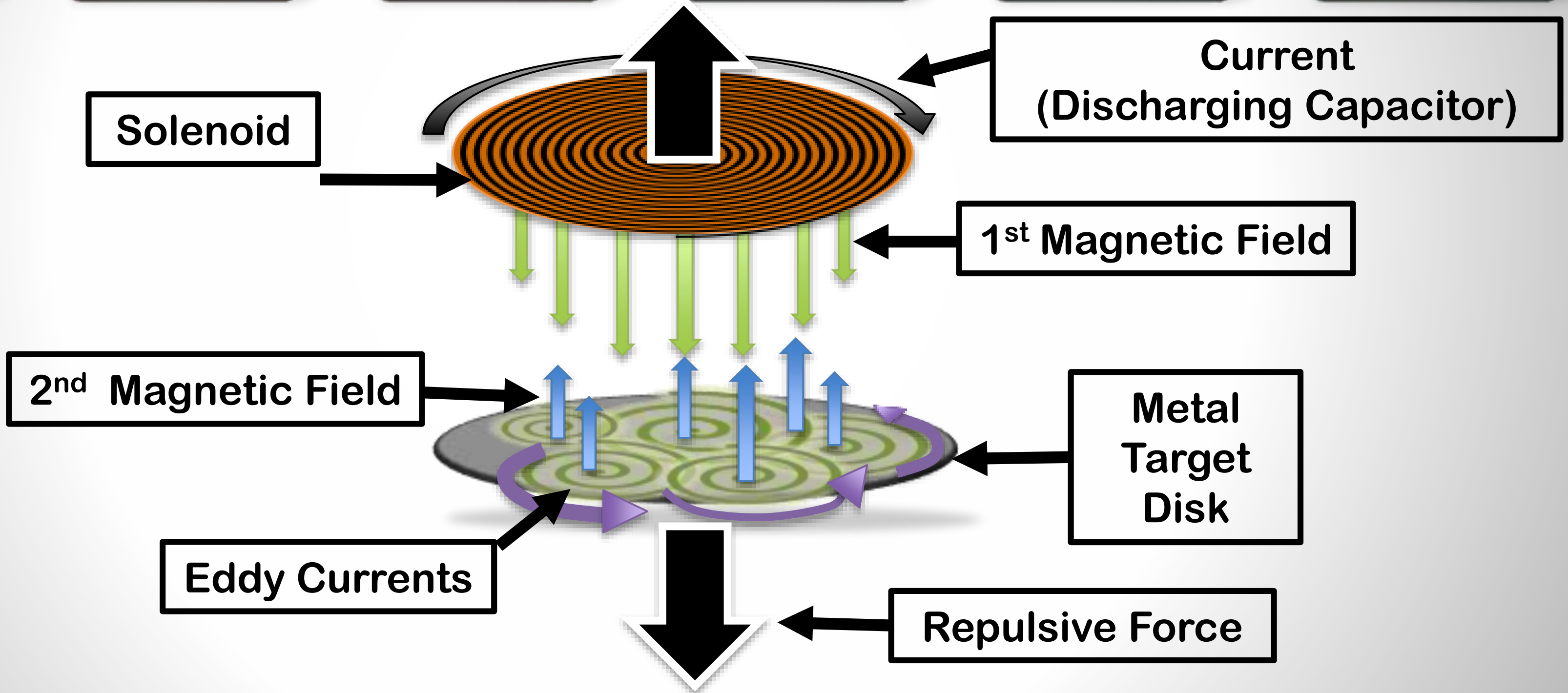
Concept of Operations



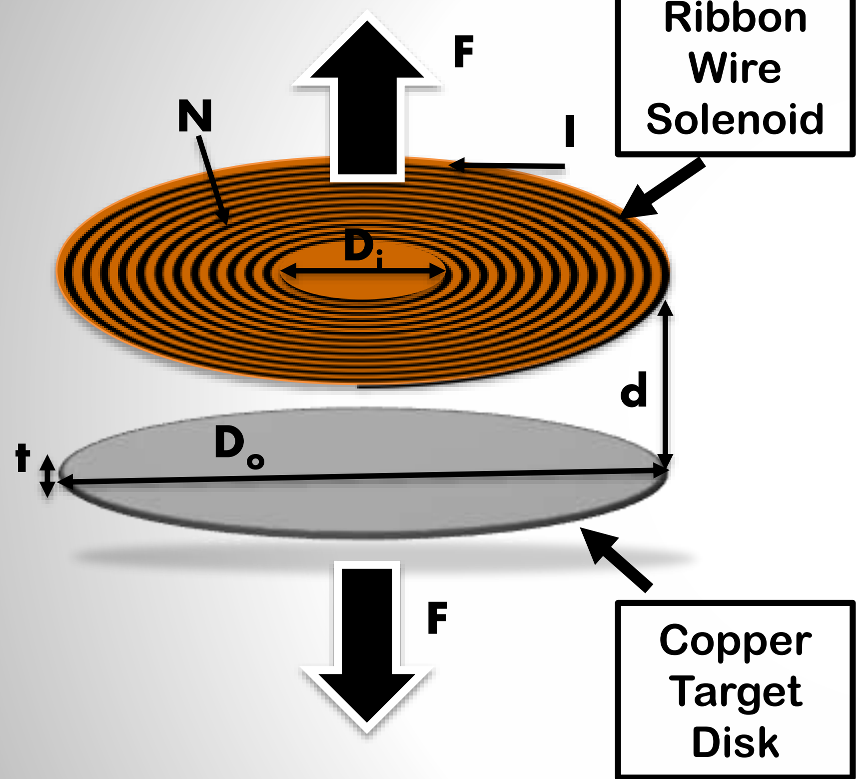
Design Solution

Theory of Design

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



Solenoid & Target Disk Design



Ribbon Wire Solenoid	
Outer Diameter (D_o)	3.0 in.
Inner Diameter (D_i)	0.50 in.
Height	0.19 in.
Number of Loops (N)	50

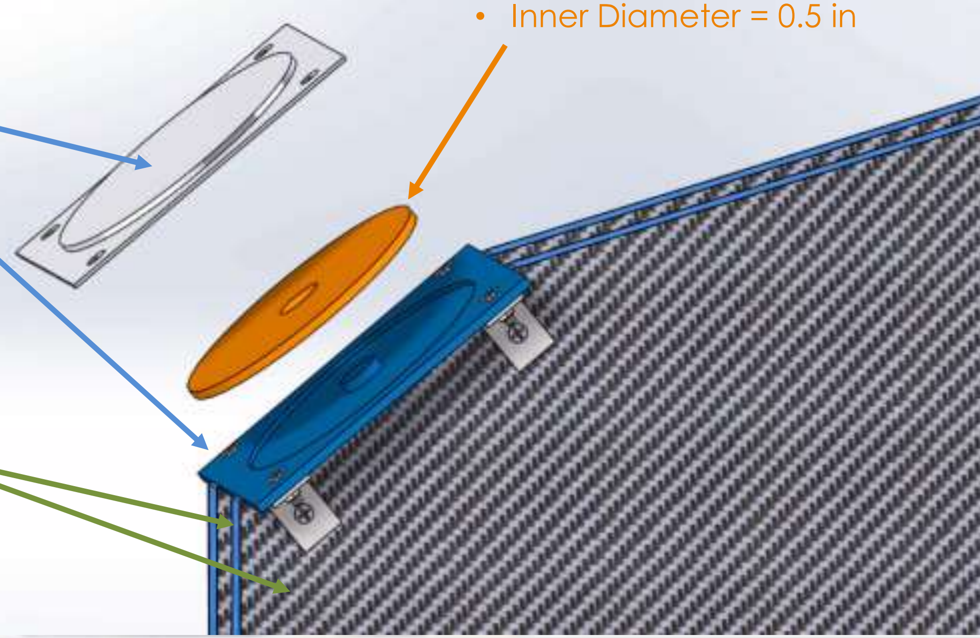
Copper Target Disk	
Gap Distance (d)	0.08 in.
Thickness (t)	0.08 in.

Project Description | **Design Solution** | Verification & Validation | Planning

Final Integrated Design

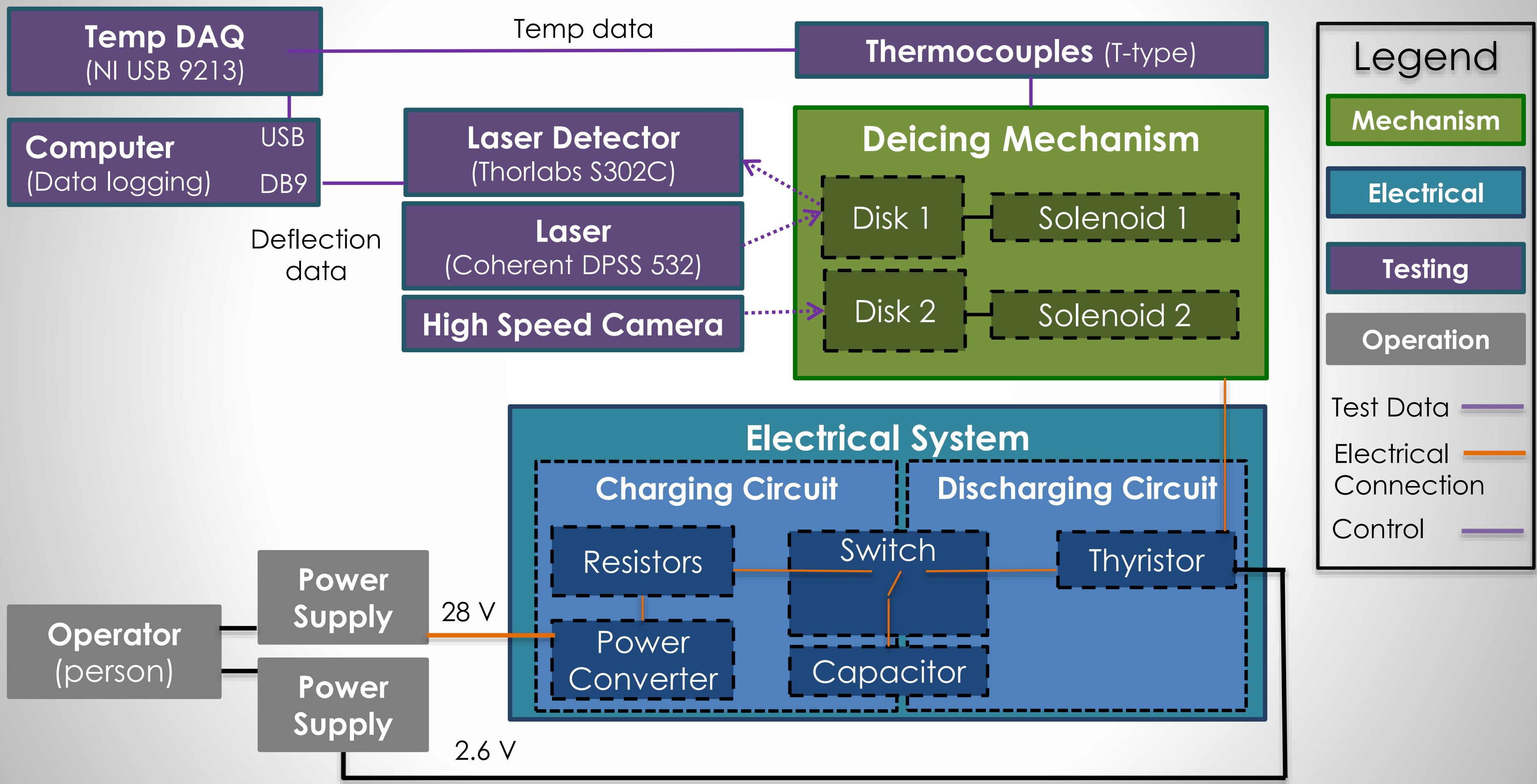
Top Plate & Base Plate
- High Density Polyethylene
- Thickness: 0.04 in ± 0.01 in
- Allow for 22% growth in solenoid diameter

Solenoid
- Outer Diameter = 3 in
- Inner Diameter = 0.5 in



2 Dragon Plate Support Structures per Solenoid
- Carbon Fiber Sandwich with Foam Core
- Each Carbon Fiber Plate Thickness = 0.03 in
- Foam Core Thickness = 0.5 in

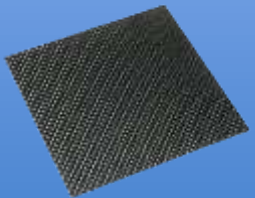
Functional Block Diagram



Critical Project Elements

Structural & Force Models

Ice Rupture



Test Section & Housing Unit

Solenoid Design

Solenoid

Target Disk

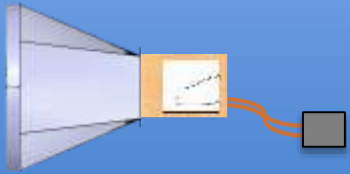
Electrical & Software

Circuitry & Power

Software

Testing with Wind

Wind Speed



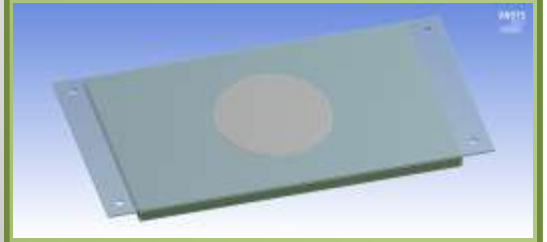
Test Setup

Design Requirements & Satisfaction

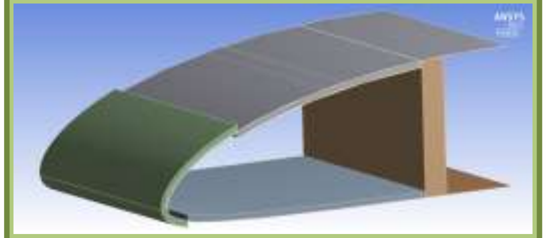
CPE 1 – Structural Integrity

FR.1 The full-scale system shall be integrable with the Orion UAV.	
DR.1.1	The **installation** of the system shall **not damage or degrade** the structural integrity of the wing.
DR.1.2	The **operation** of the system shall **not damage or degrade** the structural integrity of the wing.
FR.2 The prototype shall remove ice on wing section.	
DR.2.1	The prototype shall be **capable of removing ice** built-up to 3/8 in thick on test section.

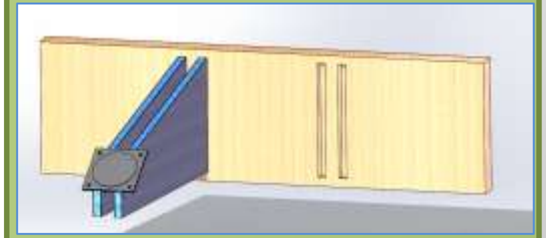
Flat Plate Analysis



Curved Section Analysis



Housing Unit Analysis

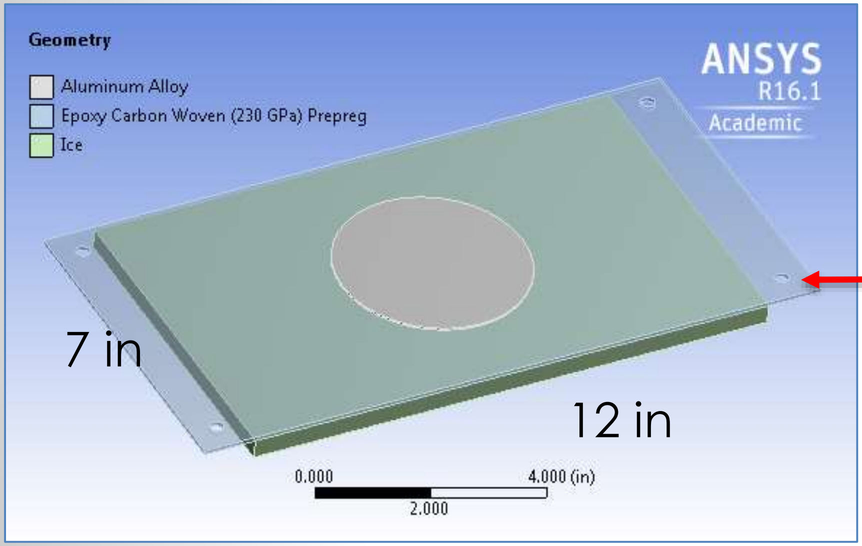


Project Description | **Design Solution** | Verification & Validation | Planning

Flat Plate Analysis – Setup

Goal – Confirm model with test data to prove level 3 design can meet requirements

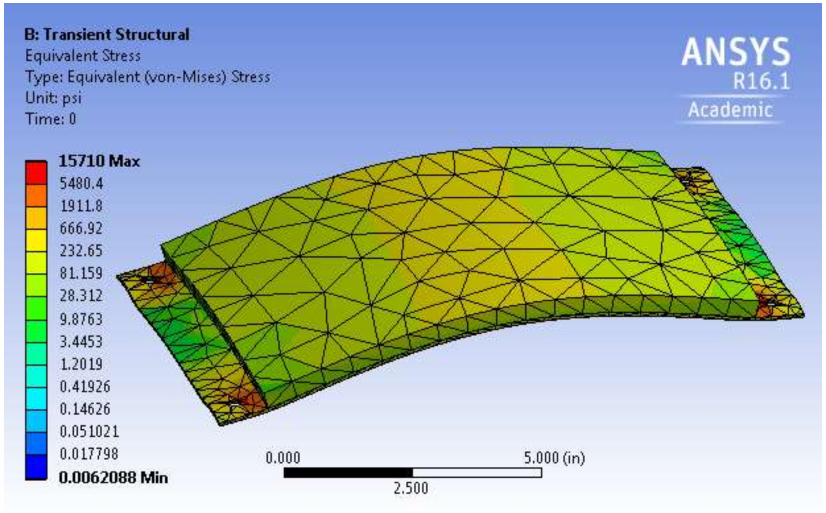
ANSYS Model Setup



Flat Plate Setup

Flat Plate Analysis – Ice Rupture

ANSYS Model



Used to correct material properties for future curved models

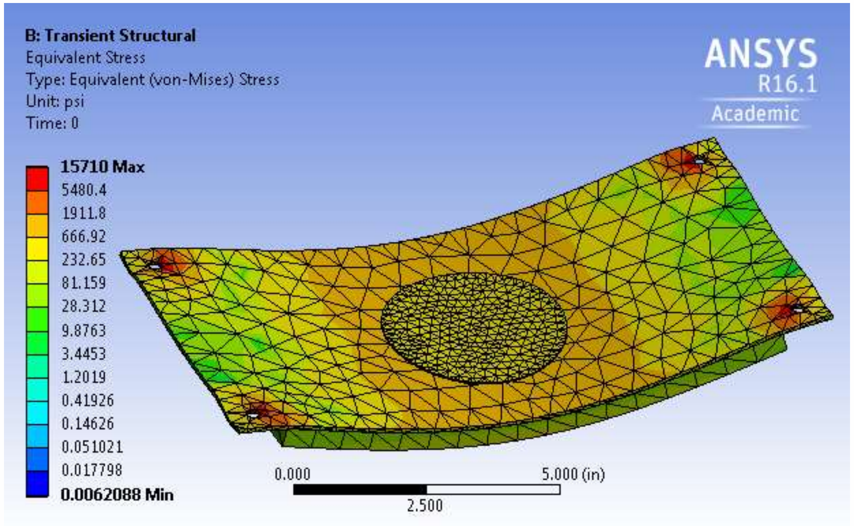
Analysis Method	F_{req} for Ice Rupture	Tensile Strength of Ice
ANSYS – from researched material properties	34 lb	203 psi
Testing Data	57 lb	Not measured
ANSYS – corrected model	57 lb	347 psi

✓ **Required volume of ice on test section can break with determined force**

Project Description | **Design Solution** | Verification & Validation | Planning

Flat Plate Analysis – Carbon Fiber

ANSYS Model



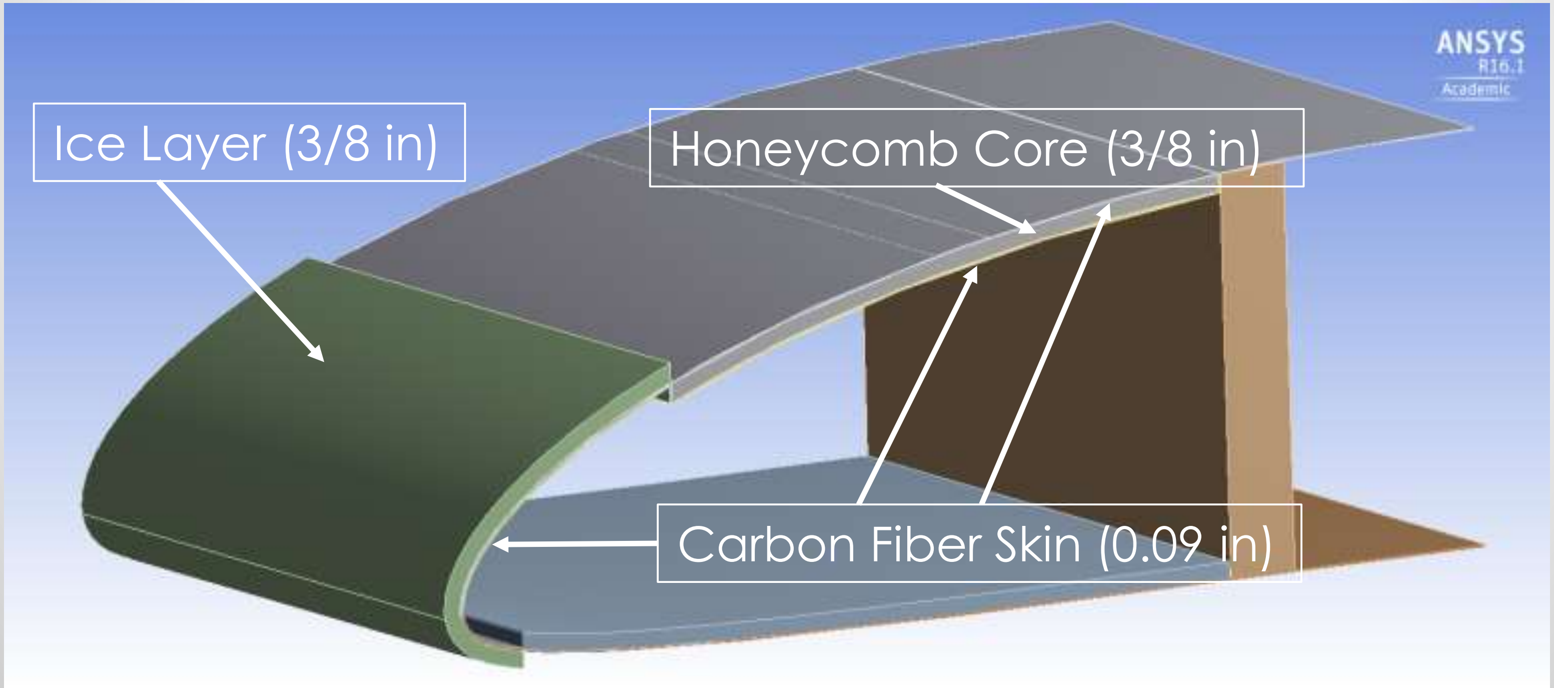
Analysis Method	Force	τ_{calc}		τ_{allow}	σ_{calc}		σ_{allow}
ANSYS Model	57 lb	58.2 psi	<	125 psi	15.7 ksi	<	72.5 ksi

✓ **Force required to break ice will not damage flat plate test section**

Curved Test Section Model

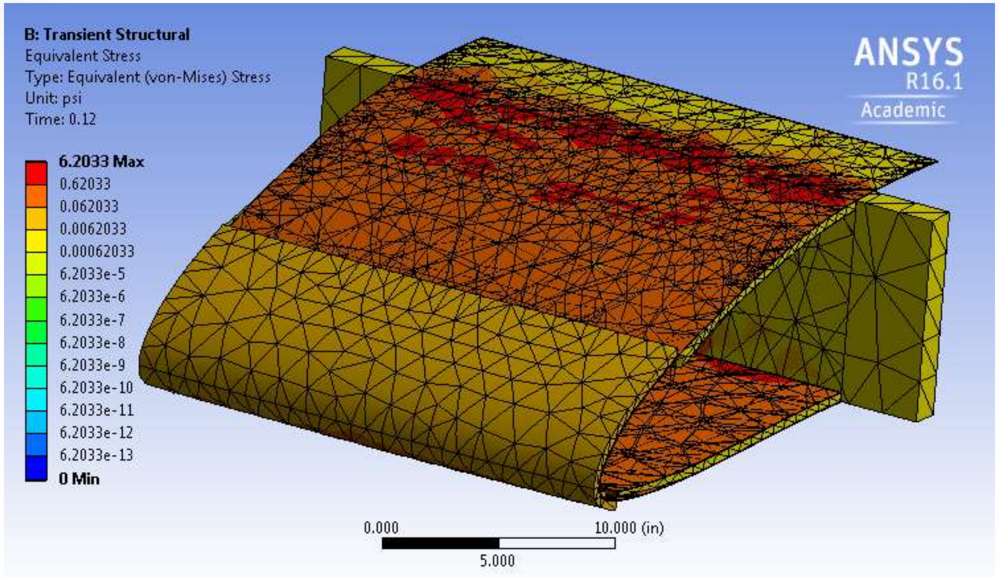
Goal – Knowing model is verified with test data from flat plate model, show that level 3 test section can withstand force required using ANSYS

DAE11 ANSYS Model



Project Description | **Design Solution** | Verification & Validation | Planning

Curved Test Section Model Analysis



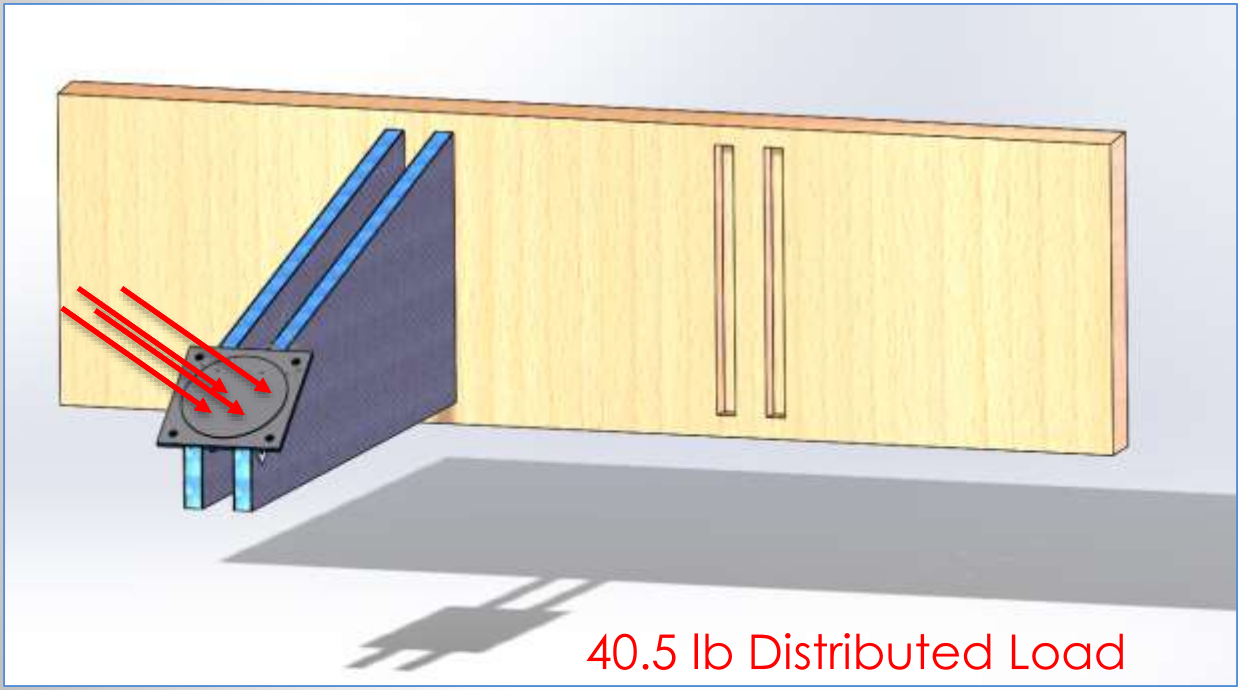
Analysis Method	Force	τ_{calc}		τ_{allow}	σ_{calc}		σ_{allow}
ANSYS Model	40.5 lb	58.2 psi	<	125 psi	15.7 ksi	<	72.5 ksi

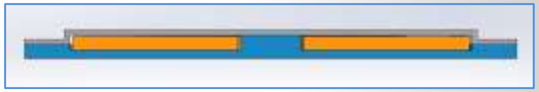
✓ **Force required to break ice will not damage DAE11 wing section**

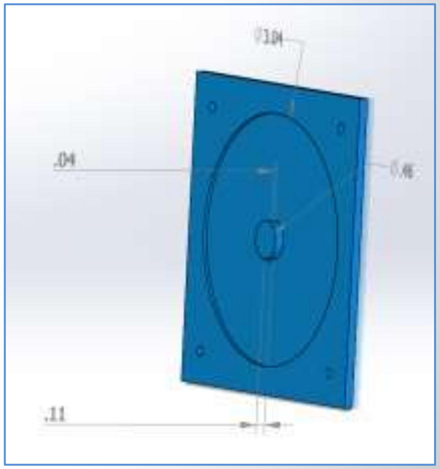
Housing Unit Model

Goal – Show that reaction force does not damage internal support structure

ANSYS Housing Unit Model





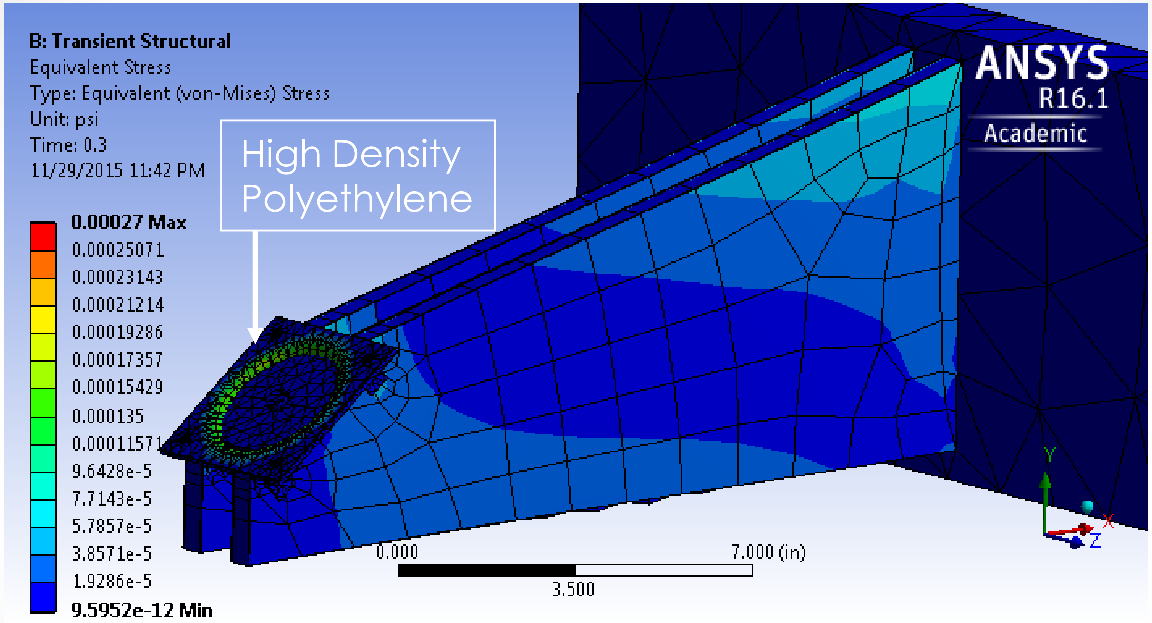


Note: dimensions in [in]

Project Description | **Design Solution** | Verification & Validation | Planning

Housing Unit Model Analysis

ANSYS Housing Unit Model



Analysis Method	Force	τ_{calc}		τ_{allow}	σ_{calc}		σ_{allow}
Carbon Fiber Analysis	41 lb	$1.4 * 10^{-3}$ psi	<	3.0 ksi	$0.27 * 10^{-3}$ psi	<	4.6 ksi

✓ **Force required to break ice will not damage flat plate test section**

Structural Integrity Conclusions

FR.1 The full-scale system shall be integrable with the Orion UAV.	
DR.1.1	The installation of the system shall not damage or degrade the structural integrity of the wing.
DR.1.2	The operation of the system shall not damage or degrade the structural integrity of the wing.

- ✓ Wing structure can withstand required force
- ✓ Internal support can withstand reaction forces and moments

FR.2 The prototype shall remove ice on wing section.	
DR.2.1	The prototype shall be capable of removing ice built-up to 3/8 in thick on test section.

- ✓ Force required to remove ice modeled for flat plate and test section
- ✓ Force required to remove ice tested for flat plate

CPE 2 – Solenoid Design

FR.1 The full-scale system shall be integrable with the Orion UAV.	
DR.1.2	The de-icing mechanism shall be integrable with the DAE11 airfoil.
FR.2 The prototype shall remove ice.	
DR.2.1	The prototype shall be capable of removing 3/8 in thick ice on test section.

Solenoid Size Test

- Volume constraints

Solenoid COMSOL Model

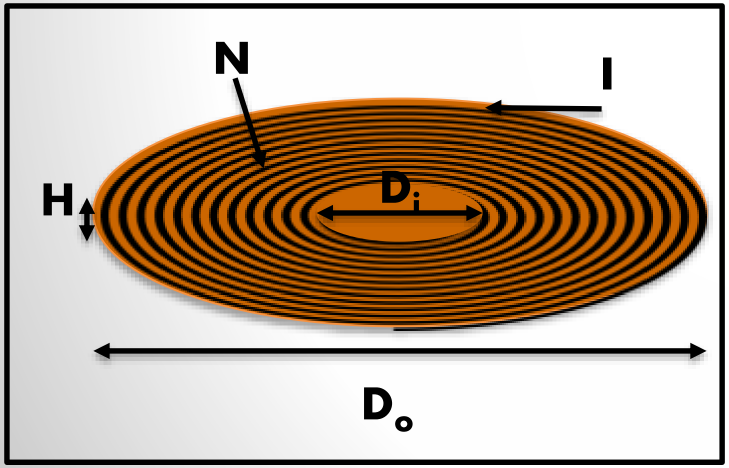
- Methods
- Model limitations

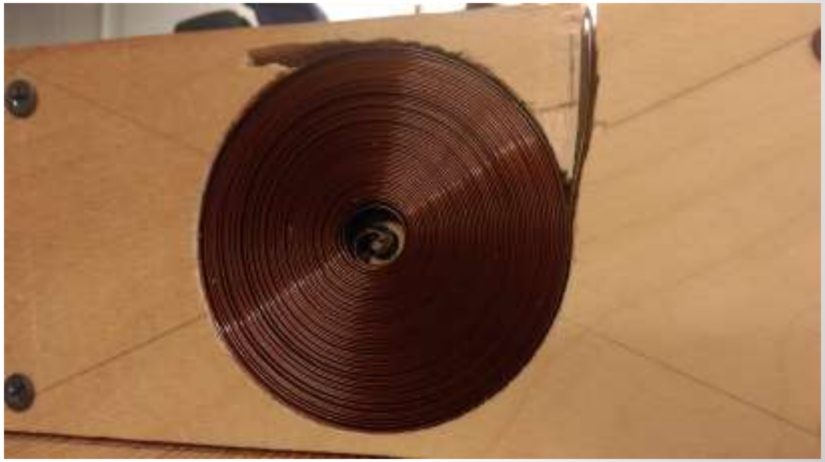
Design and Validation

- Model Adjustments
- Empirical testing

Solenoid Size Test

Ribbon Wire Solenoid	
Outer Diameter (D_o)	3.0 in.
Inner Diameter (D_i)	0.50 in.
Height	0.19 in
Number of Loops (N)	50





Project Description | **Design Solution** | Verification & Validation | Planning

Solenoid COMSOL Model

Input Parameters

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

Simplifies to 4 parameters

- J_e – External current density
- A – Magnetic potential
- σ – Electric conductivity
- μ – Magnetic permeability

System of Equations

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

$$B = \nabla \times A$$

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

Goal

- B – Magnetic field density
- F – Force $\geq 40.5\ lbs$

COMSOL Model - Best Case

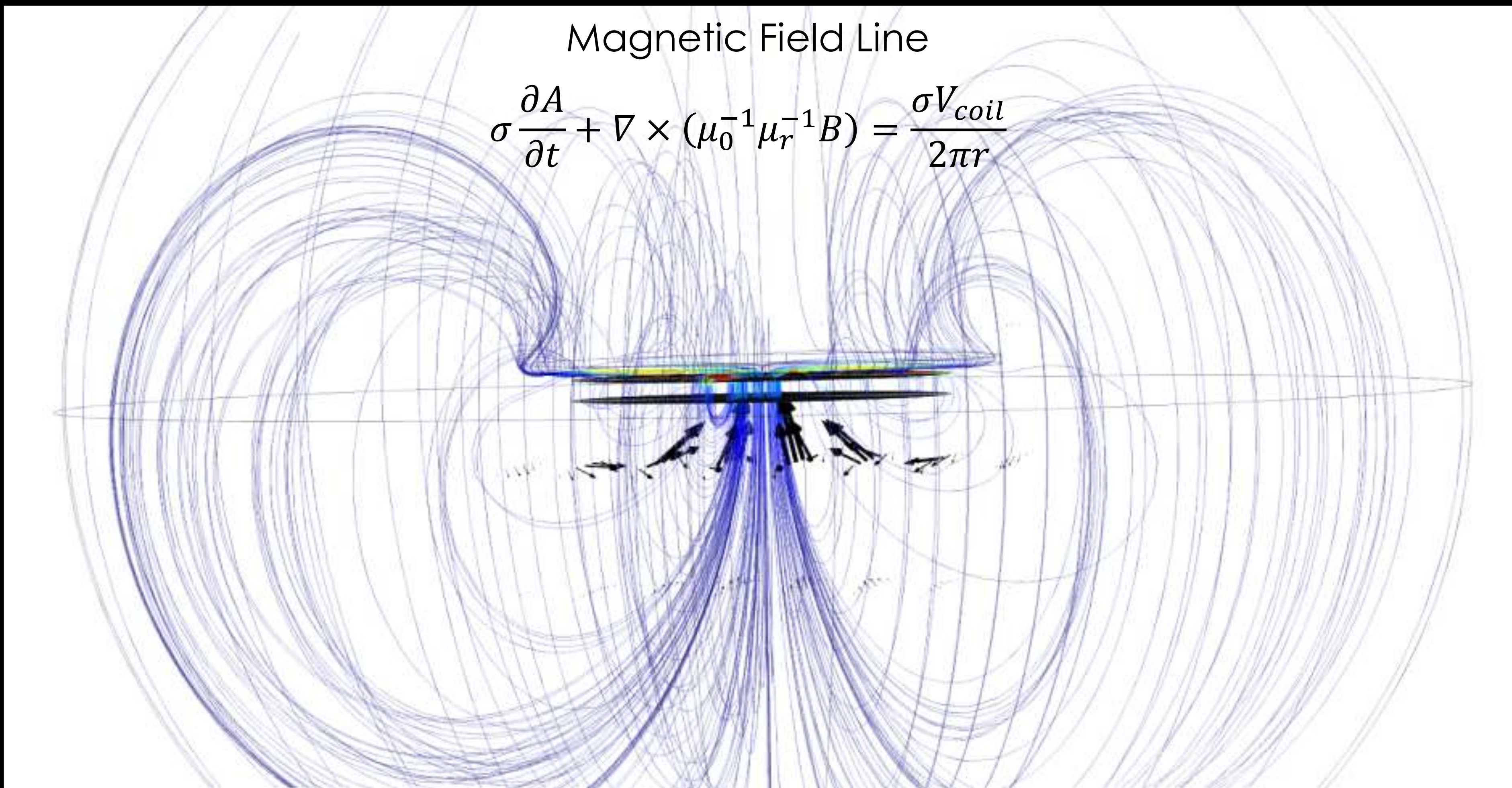
Solenoid Parameter	Value
Outer diameter	3.0 in.
Inner diameter	0.04 in.
Height	0.19 in.
Wire thickness	0.03 in.
Number of turns	36
Voltage	1000 V

Target Disk Parameter	Value
Gap between solenoid and disk	0.08 in.
Disk thickness	0.08 in.

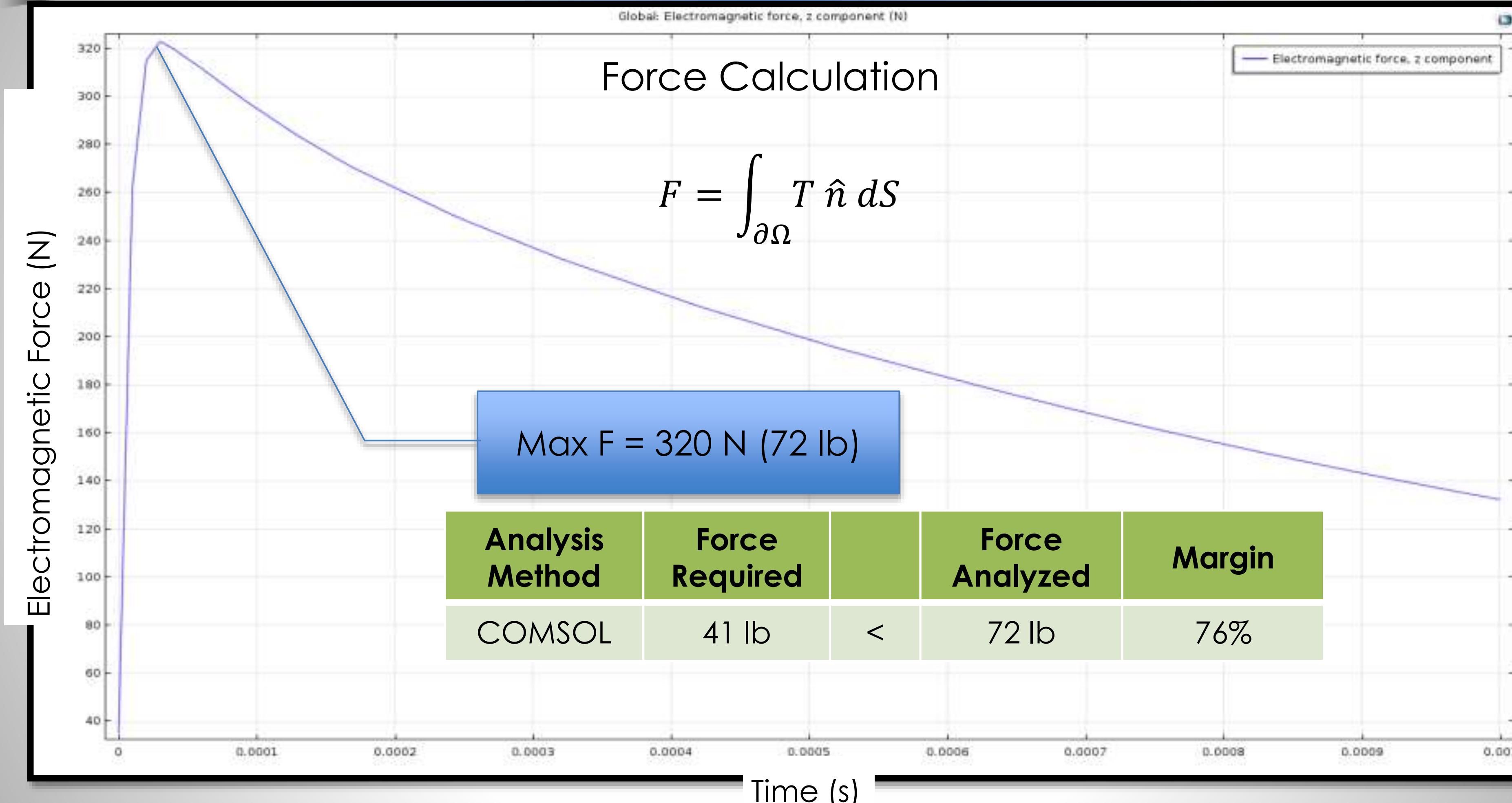
Solenoid COMSOL Model

Magnetic Field Line

$$\sigma \frac{\partial A}{\partial t} + \nabla \times (\mu_0^{-1} \mu_r^{-1} B) = \frac{\sigma V_{coil}}{2\pi r}$$



Solenoid COMSOL Model



Force Calculation

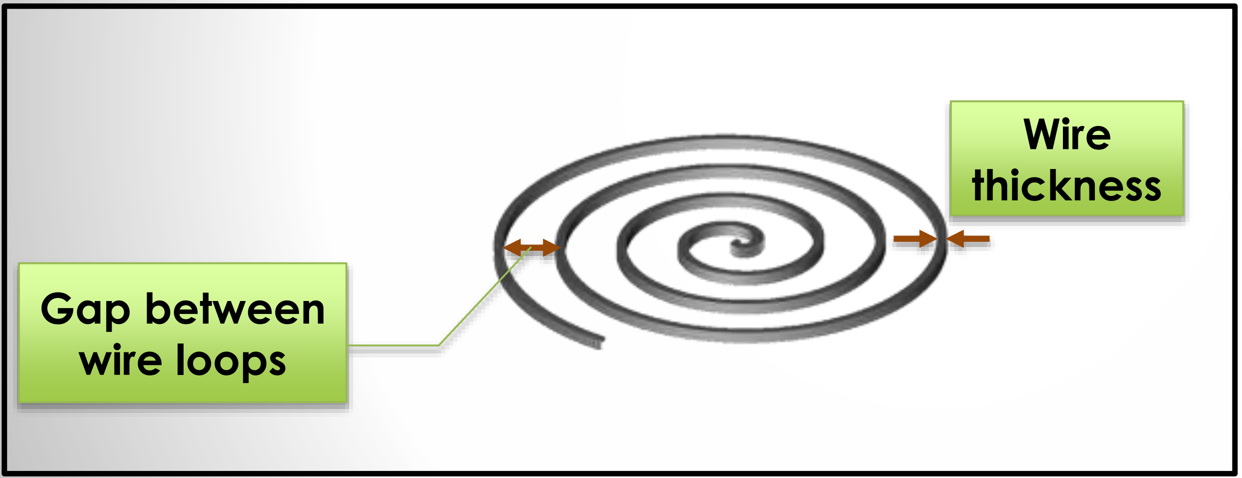
$$F = \int_{\partial\Omega} T\,\hat{n}\,dS$$

Analysis Method	Force Required		Force Analyzed	Margin
COMSOL	41 lb	<	72 lb	76%

Model Limitations

Geometric Constraints

Using 3 in. outer diameter:
- Gap between wire loops > 0.007 in
  - Resolution too high to process



Design and Validation

Parameter	Model Value	Manufacturable Value
Outer diameter	3.0 in.	3.00 in.
Inner diameter	0.04 in.	0.10 in.
Height	0.19 in.	0.19 in.
Wire thickness	0.03 in.	0.03 in.
Number of turns	36	> 50
Average gap between wire loops	0.01 in.	~0 in.

= **Refinements to model**

-Empirical Validation of Model

- Test force produced by design
- Test at capacitor discharge voltage 400-1000V to verify model at multiple points

Project Description | **Design Solution** | Verification & Validation | Planning

Solenoid Design Conclusions

FR.1 The full-scale system shall be integrable with the Orion UAV.	
DR.1.2	The de-icing mechanism shall be integrable with the DAE11 airfoil.

✓ Design fits geometric constraints

FR.2 The prototype shall remove ice.	
DR.2.1	The prototype shall be capable of removing 3/8 in thick ice on test section.

✓ Design provides enough force to remove ice

CPE 3 – Electrical & Software

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.
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.
FR.3 The full-scale system shall use less than 4 kW-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**

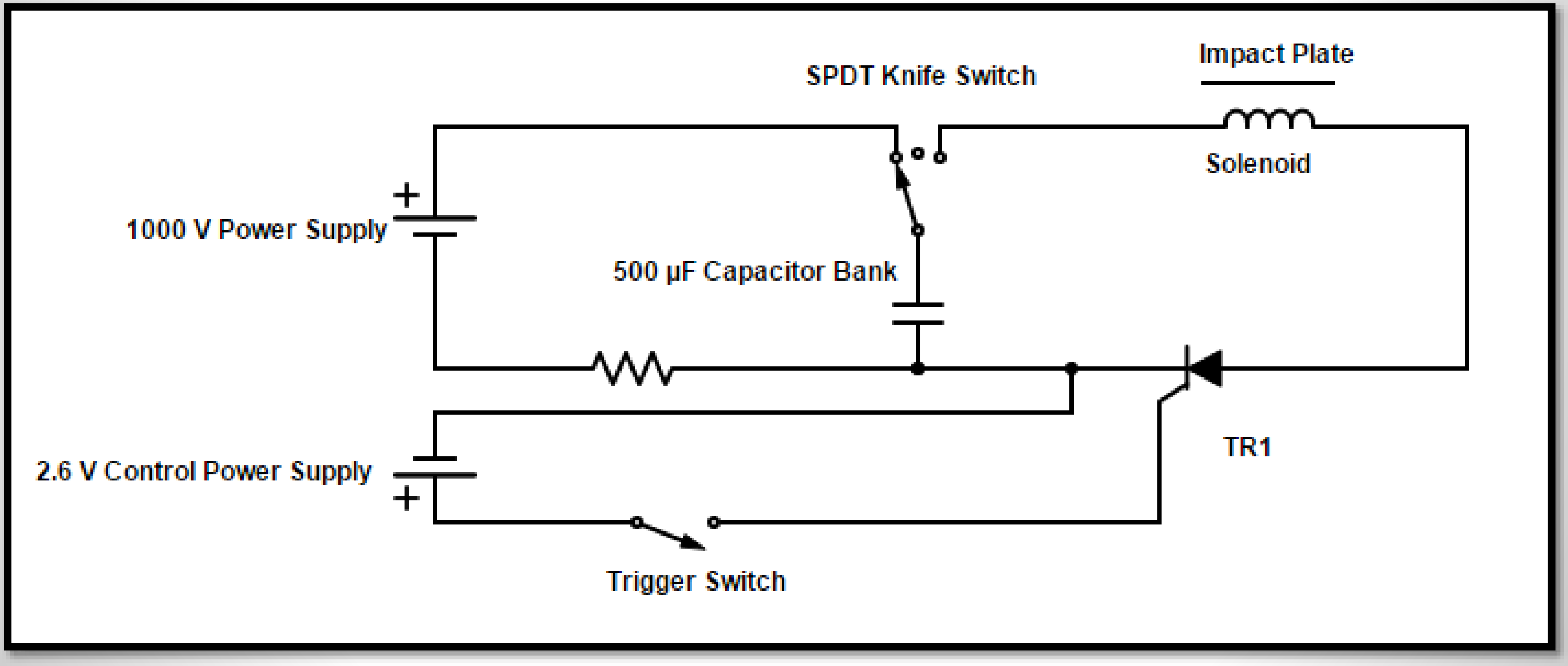
Testing Circuit

Software

Power Consumption

Safety

Testing Circuit Schematic



Safety Precautions

1. **Personal Protective Equipment**

2. **Protective Circuitry**

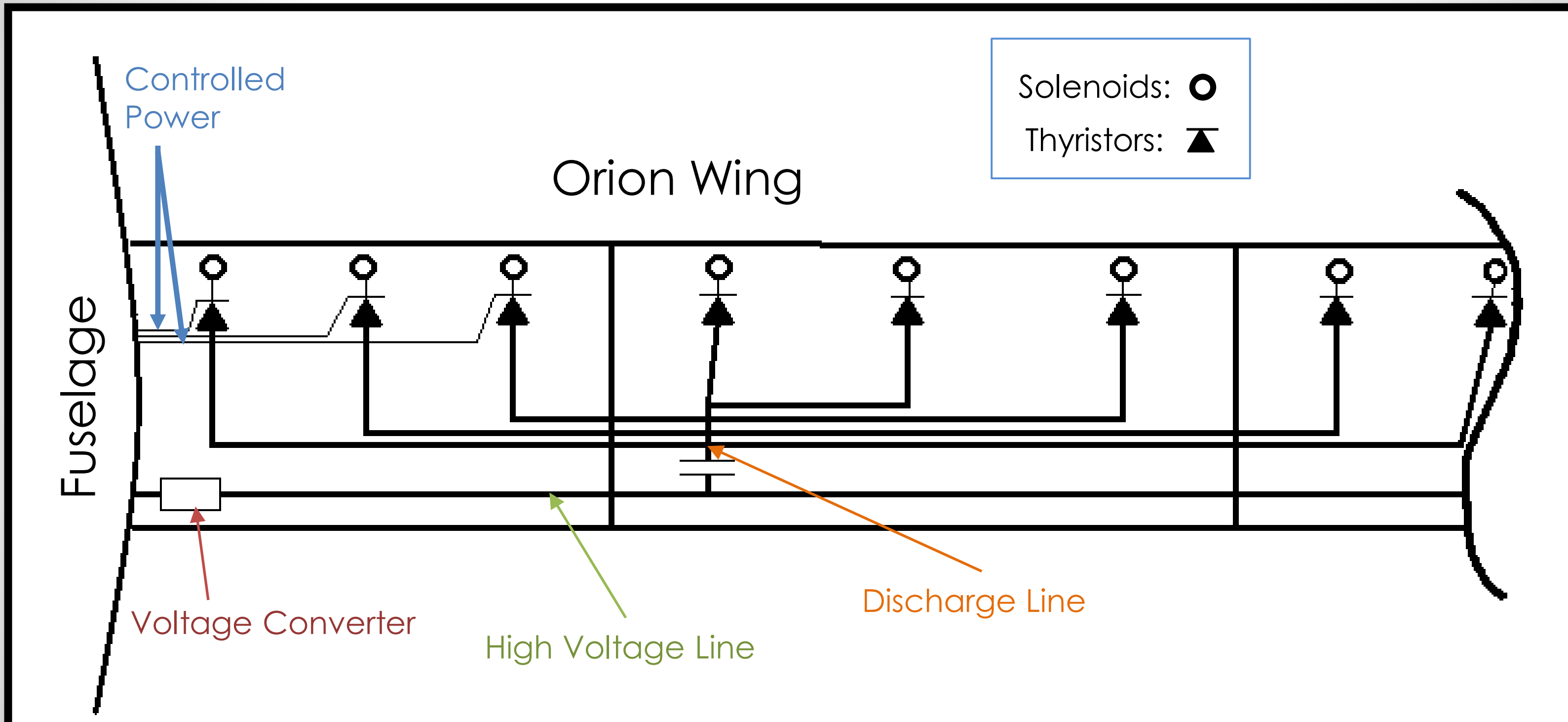
3. **Personal Protective Standards**

- 3 personnel on job at all times
- Double check that capacitors are discharged
- Never work on system while power supply is on

Project Description | **Design Solution** | Verification & Validation | Planning

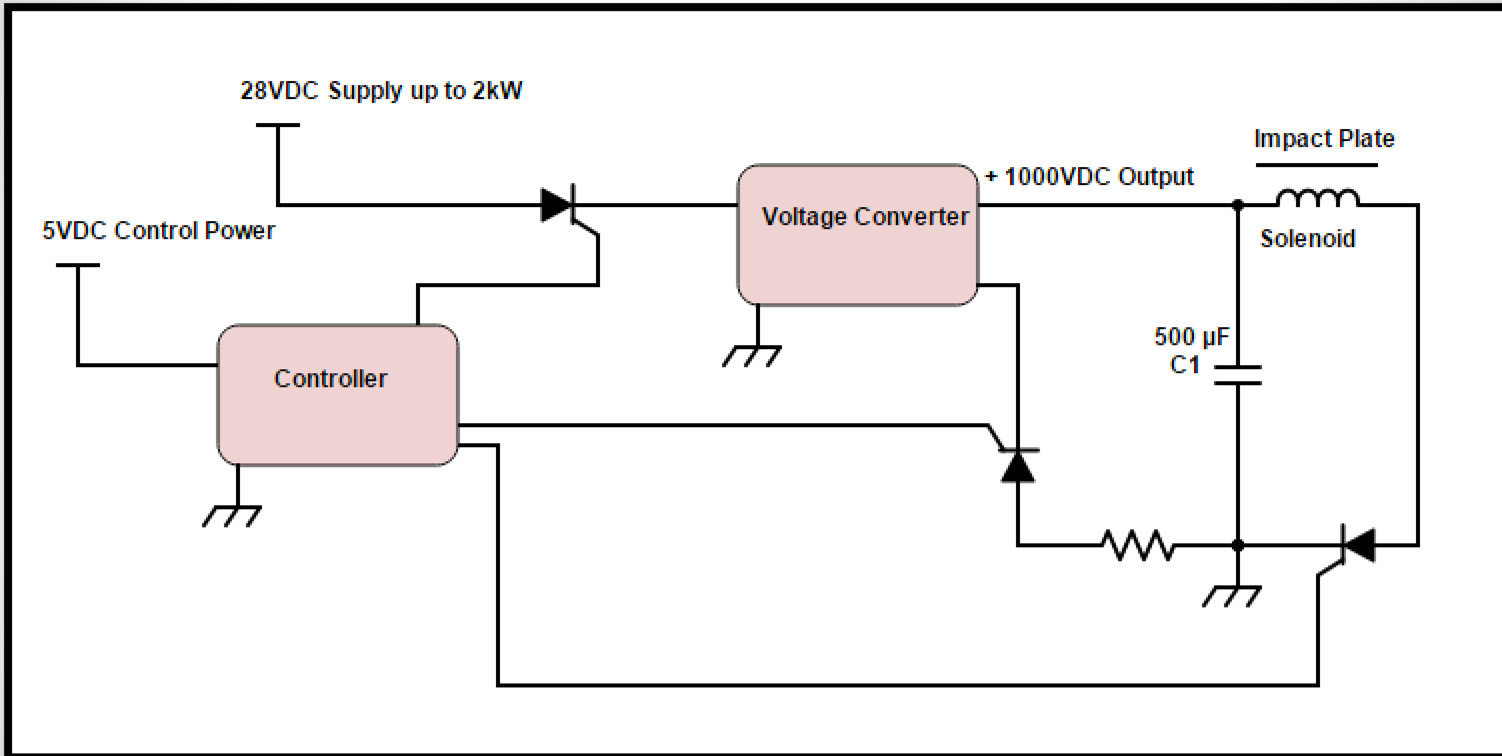
Full Scale Electrical System

For AFS full scale implementation:



Project Description | **Design Solution** | Verification & Validation | Planning

Circuit Schematic – Full Scale



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

↓

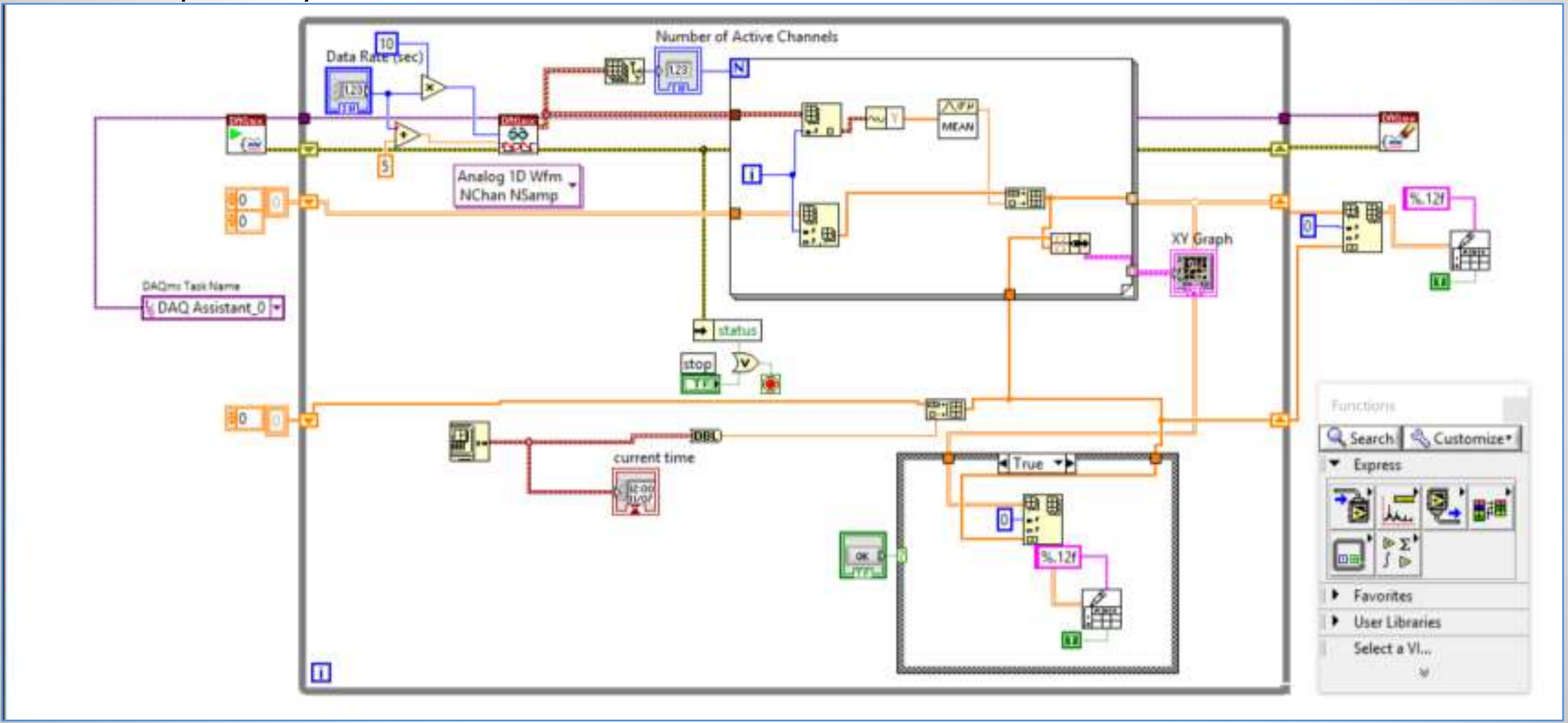
Power = 2 kW for 1 min or 100 W for 17 min

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

Software

LabView

- Thermocouple measurements
- Frequency detection



EPS Conclusions

FR.2 The prototype shall remove ice on wing section.	
DR.2.1	The prototype shall be capable of removing ice built-up to 3/8 in thick on test section.
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.

✓ Circuitry can support voltage necessary to remove ice

FR.3 The full-scale system shall use less than 4 kW-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**

✓ Power draw does not exceed 2 kW

Weight Budget

Item	Weight (lb)
Solenoids + Target Plates (76)	38.3
Housings (76)	69.3
Capacitors (10)	27.2
Wire	30.7
Voltage Converter (1)	25.0
Total	**191 lb**

- Target: 100 lbs
- Areas to decrease weight: housing unit

Risk

Risk Matrix

Likelihood	Minimal	Minor	Major	Serious	Catastrophic
Near Certainty					
Highly Likely			9, 2		
Likely		10, 1	4		3
Low Likelihood		7	6,8	5	
Extremely Unlikely					

Severity

1. Circuitry failure
2. Manufacturing ice casting structure
3. Unable to produce modeled solenoid force
4. Approval of safety plan taking too long
5. Ice casting too inconsistent for valid test results
6. Poor functionality of deflection measuring device
7. Misallocation of time
8. Cannot get trigger mechanism circuitry to work
9. Solenoid positioning does not fully remove ice
10. Manufacturing wing section incorrectly first time

Risk Mitigation

Level	Risk	Mitigation
Green	1	Buy extra circuitry to replace failed component
Yellow	2	Keep Matt Rhode in the loop during the manufacturing to help ensure that the tolerances of the mold are correctly met
Red	3	Redesign solenoid shape and circuitry
Yellow	4	Have safety plan ready for approval before start of next semester
Yellow	5	Replace or redesign problem component of ice casting trough
Green	6	Switch to off-ramp deflection measurement design
Green	7	SE and PM stay in close contact to ensure efficient use of teams time.
Green	8	Go to Trudy or Bobby for help, or use off ramp trigger design
Yellow	9	Adjust solenoid positioning
Green	10	Have enough extra materials in stock to make a second wing section

Project Description | **Design Solution** | Verification & Validation | Planning

Risk Matrix

Likelihood	Minimal	Minor	Major	Serious	Catastrophic
Near Certainty					
Highly Likely		9			
Likely	1		3		
Low Likelihood	6	4, 10	2, 5		
Extremely Unlikely		7	8		

Severity

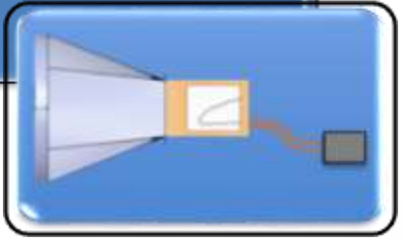
1. Circuitry failure
2. Manufacturing ice casting structure
3. Unable to produce modeled solenoid force
4. Approval of safety plan taking too long
5. Ice casting too inconsistent for valid test results
6. Poor functionality of deflection measuring device
7. Misallocation of time
8. Cannot get trigger mechanism circuitry to work
9. Solenoid positioning does not fully remove ice
10. Manufacturing wing section incorrectly first time

Verification & Validation

V&V Approach

Ice Casting

Dynamic Testing

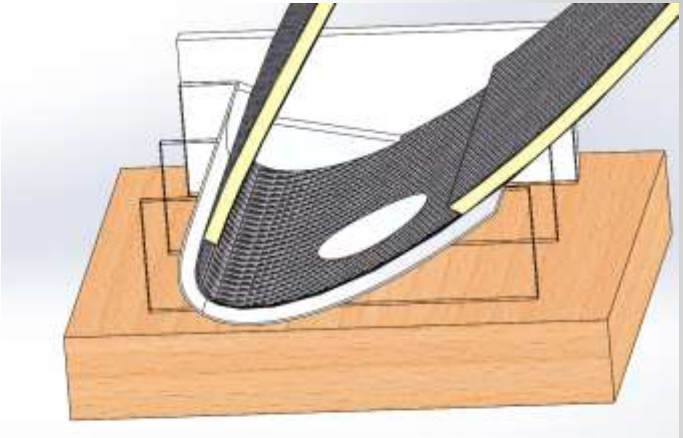


Sensors

Ice Casting

Manufacturing Trough

- Laser cut acrylic sheets in shape of DAE-11 to use as supports for trough.
- Use high density polyethylene material to create the smooth surface of the trough.
- End Caps



Ice Casting

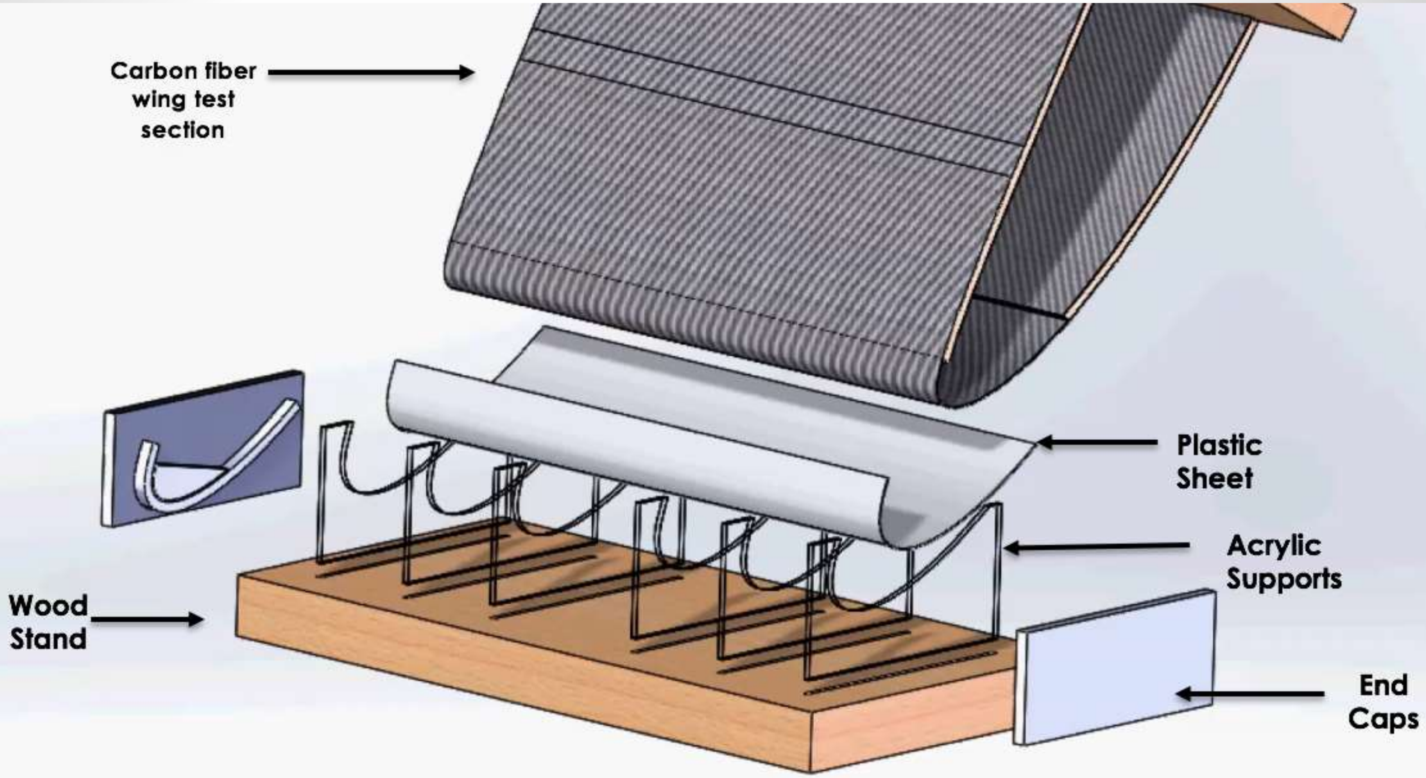
- Coat the smooth material with wax
- Use end caps to hold the test
- section in place
- Assemble the trough and test section
- Pour water
- Wait for water to freeze

Removing Test Section from Trough

- Remove end caps to pull out the test section

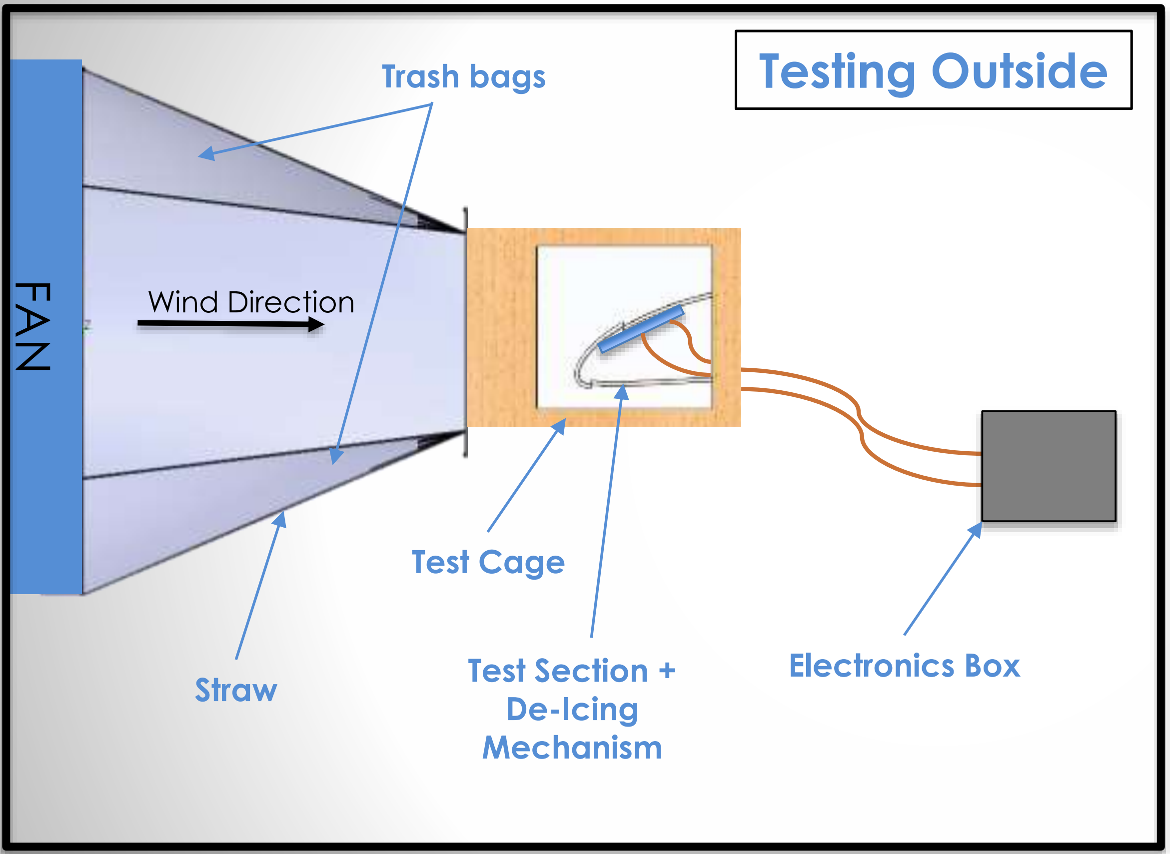
Project Description | Design Solution | **Verification & Validation** | Planning

Ice Casting Trough



End caps hold test section 3/8" higher than plastic sheet.

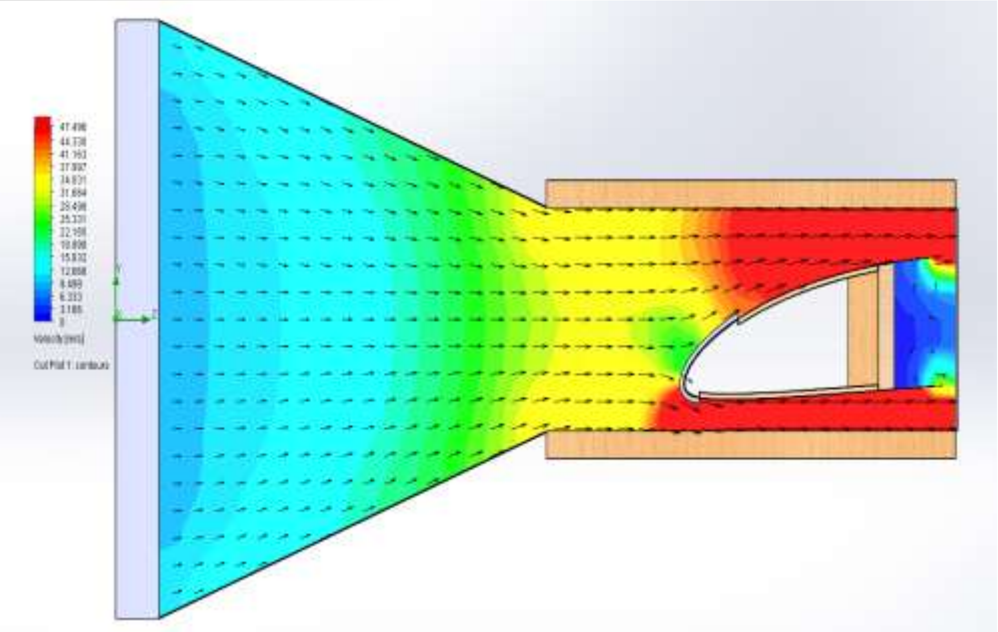
High Wind Speed Test - Set-Up



- Create converging nozzle
  - Trash bag + flow straighteners (straws)
- Rectangular area exit = 10" by 24"
- Fan: 13,200 CFM
  - Use converging nozzle to reach testing speed = 75 mph at Leading Edge
- Testing outside of ITLL

Project Description | Design Solution | **Verification & Validation** | Planning

Flow Simulation



- Flow simulation created in Solid Works.
- For testing we need to be at 75 mph.
- Flow simulation showed flow around leading edge is about 75 mph (± 4 mph).

High Wind Speed Test - Sensors

Testing Needs:		Selected Sensors:
Temperature Range		**T-Type Thermocouples** • Range: -200˚C to 200˚C • Measure temperature inside of the wing test section and room temperature.
Deflection		**High Speed Camera + Deflection Test** • Record testing use frames to verify the deflection of the carbon fiber. • Deflection Test using laser measurements
Amperage		**High Voltage Multimeter** • Measure amperage in the circuit
Testing Speed		**Pitot Tube Probe + Manometer** • Pitot Tube: Dwyer 160-18 Stainless Steel • Manometer: PVM 100 Micromanometer • Used to measure wind speed near the leading edge.

Planning

Organizational Chart

Resources

- Advisor: Joe Tanner
- Customer: Ellis Langford, Ed Wen

Project Leads

- Project Manager: Libby Thomas
- Systems Engineer: Drew Moorman

Tech Leads

- Solenoid Lead: Andre Litinksy
- Manufacturing Lead: Jon Eble
- Mission Assurance Lead: Kelly Allred
- FO/Testing Lead: Jacquie Godina
- Electrical Lead: Nicole Ela
- SO/Software Lead: Runnan Lou
- Structural Lead: Colin Zohoori

Work Breakdown Structure

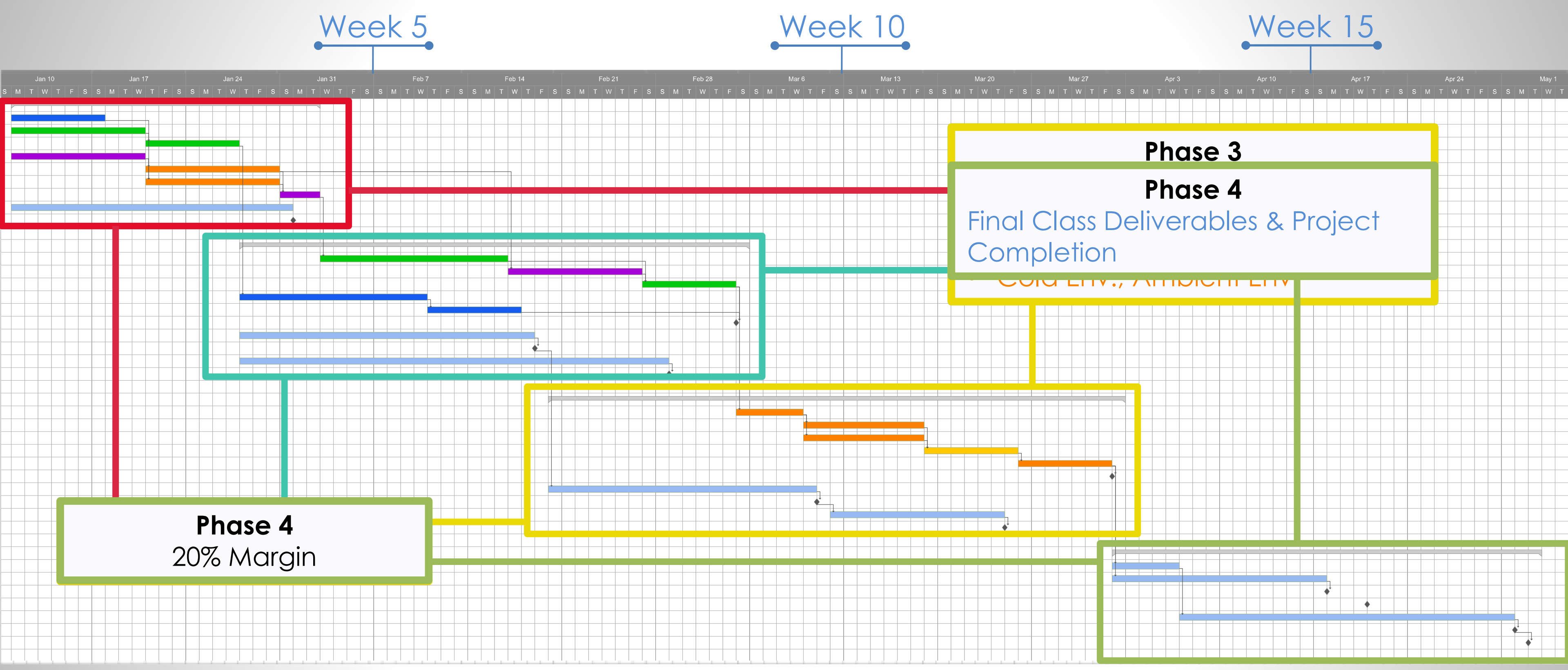
AESIR

- **Test Section**
  - Surface ANSYS Model
  - Housing Unit ANSYS Model
  - Manufacture DAE11 Molds
  - Manufacture DAE11 Wing Section
  - Manufacture Housing Unit
  - Test Section Integration
- **Solenoid & Circuit**
  - Solenoid & Target Disk Force Model
  - Circuit Schematic, Component Specs, Power Model, Assembly
  - Software (LabVIEW)
  - Safety Checklist & Equipment
  - Full Scale Model & Analysis for AFS
- **Testing Apparatus**
  - Model Ice Casting Apparatus
  - Manufacture Ice Casting Apparatus
  - Manufacture Wind Tunnel Test Cage & Table Mount
  - Acquire, Program, Set-Up Sensors
- **Testing**
  - Solenoid & Circuit Tests
  - Flat Plate Actuation Tests (Static)
  - Flat Plate Actuation Tests (Dynamic)
  - Fully Integrated Actuation Tests (Static)
  - Fully Integrated Actuation Tests (with Wind)

Complete | To Be Completed

Project Description | Design Solution | Verification & Validation | **Planning**

Work Plan



= Testing Equipment = Test Section = Circuit/Solenoid = Testing = Class Deliverable

Project Description | Design Solution | Verification & Validation | **Planning**

Test Plan

Flat Plate Test

Phase 1

Jan 21 – Jan 30

Description

- Verify circuitry works
- Bend flat plate to check force produced with single solenoid
- With and without wind

Full Assembly Test

Phase 3

March 5 – March 18

Description

- Cycle de-icing mechanism to check functionality
- With and without ice to check deflection

Dynamic Test

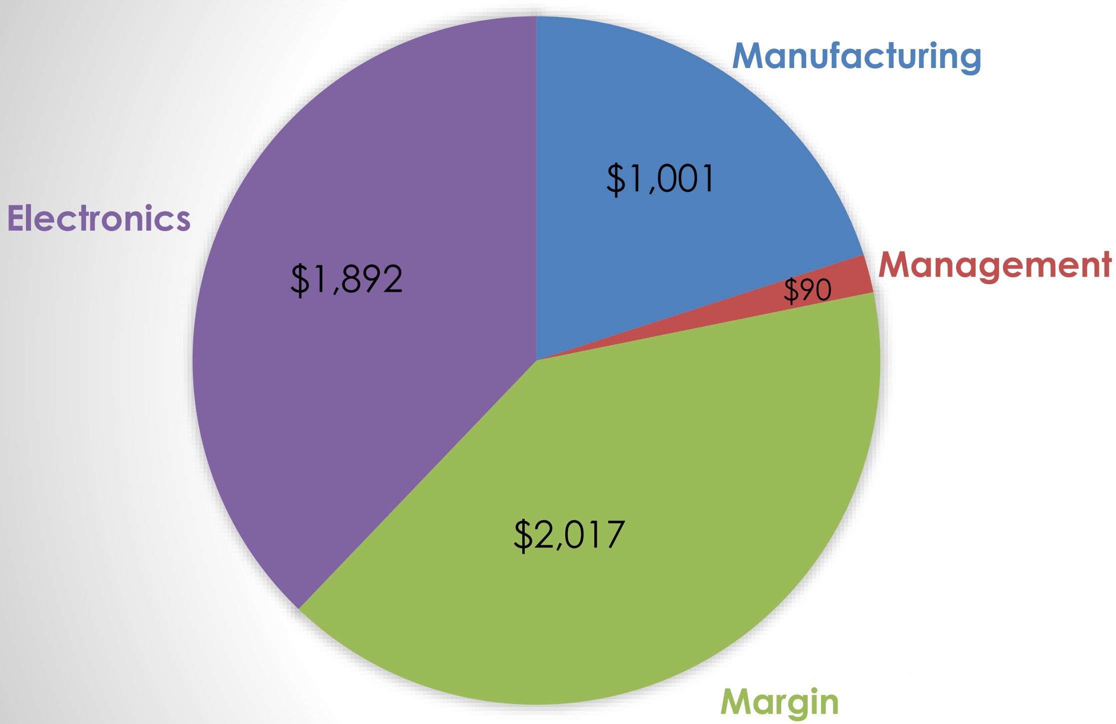
Phase 3

March 5 – March 18

Description

- Cycle de-icing mechanism with cast ice
- Simulated wind from a fan.

Cost Plan



Manufacturing
- Test Section
- Housing Unit
- Ice Cast Mold

Electronics
- Circuit
- Solenoid

Management
- Gantt Chart

Total Expenses: $2,983

Margin: $2,017

References

[1]"Ice on the wing of the NASA Twin Otter," UCAR, 2005 URL: http://www.ucar.edu/communications/staffnotes/0412/ice.html [citied 11 Oct. 2015].

[2]"Deice Disconnect" Flight Safety, 2008 URL: flightsafety.org [cited 11 Oct. 2015].

[3]"AURORA ORION UAV COULD CUT ISR COSTS 80%," Aerospace Blog, 30 Nov. 2010, URL: https://aerospaceblog.wordpress.com/2010/11/30/1747 [cited 11 Oct. 2015].

[4]"Eddy Current," URL: http://www.acndt.com/images/EddyCurrentPic1.jpg [cited 10 Oct. 2015].

[5]Ashby, M. F., and David R. H. Jones. *Engineering Materials 2: An Introduction to Microstructures, Processing, and Design*. 1st ed. Vol. 39. Oxford: Pergamon, 1986. Print.

[6]Chamis, Christos C. "NASA TECHNICAL NOTE." *ANALYSIS OF THE THREE-POINT-BEND TEST FOR MATERIALS WITH UNEQUAL TENSION AND COMPRESSION PROPERTIES* (1974): n. pag. NASA. Web.

[7] Roark, Raymond J., and Warren C. Young. *Roark's Formulas for Stress and Strain*. 7th ed. New York: McGraw-Hill, 1989. Print.

[8] Roark, Raymond J., and Warren C. Young. *Roark's Formulas for Stress and Strain*. 7th ed. New York: McGraw-Hill, 1989. Print.

[9] Hibbeler, Russell C. *Mechanics of Materials*. Upper Saddle River, NJ: Pearson Prentice Hall, 2007. Print.

[10] Roark, Raymond J., and Warren C. Young. *Roark's Formulas for Stress and Strain*. 7th ed. New York: McGraw-Hill, 1989. Print.

[11]"Solenoid-1," 2008, URL: https://commons.wikimedia.org/wiki/File:Solenoid-1.png [cited 12 Oct. 2015].

[12]"Solenoid (Electromagnet) Force Calculator." *Solenoid (Electromagnet) Force Calculator*. N.p., n.d. Web. 13 Oct. 2015.

[13]"Electronics Fundamentals: Transformer," 2015, URL: http://www.jameco.com/Jameco/workshop/learning-center/transformer.html [cited 12 Oct. 2015].

[14]"Ribbon Solenoid," [cited 12 Oct. 2015].

References

http://aviationweek.com/defense/aurora-claims-endurance-record-orion-uas
https://dragonplate.com/ecart/cartView.asp?rp=product%2Easp%3FpID%3D699
http://www.usplastic.com/catalog/item.aspx?itemid=34431&catid=705
http://www.omega.com/pptst/SA1.html
http://www.qualityinstruments-direct.com/product/dwyer-160-18-pitot-tube-velometer-18-inches
http://www.thorlabs.us/newgrouppage9.cfm?objectgroup_id=3333&pn=S302C
https://www.coherent.com/products/?765
http://www.tapplastics.com/product/plastics/plastic_sheets_rolls/ldpe_sheets/410
http://www.onlinemetals.com/merchant.cfm?pid=21806&step=4&id=1586&gclid=CL6K4Zm4m8kCFZOBaQodEkwKCA
https://www.metalsdepot.com/products/alum2.phtml?page=flat&LimAcc=%20&aident=
http://www.jegs.com/i/Meguiar's/538/M0811/10002/-1?CAWELAID=230006180002770392&CAGPSPN=pla&catargetid=230006180000848433&cadevice=c&gclid=CI2i5MbAm8kCFQ6maQodDvAMyw
http://www.fibreglast.com/product/Nomex_Honeycomb_1562/Vacuum_Bagging_Sandwich_Core
http://www.fibreglast.com/product/Nylon_Released_Peel_Ply_582/Vacuum_Bagging_Films_Peel_Ply_Tapes
https://www.acpsales.com/Quick-Locks.html
http://www.amazon.com/Copper-Sheet-Metal-12/dp/B00AKMNNX4
http://www.globalindustrial.com/p/hvac/fans/blower/global-42-portable-blower-fan-belt-drive-600554
http://www.homedepot.com/s/plywood?NCNI-5
http://www.homedepot.com/s/2+by+4+wood?NCNI-5
https://www.rockwestcomposites.com/cart
http://www.usplastic.com/catalog/item.aspx?itemid=34431&catid=705

Questions?

Backup Slides

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 de-ice the wing section.

Function Requirement 1

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

- **DR.1.1** The full-size system shall weigh less than **100** lb
- **DR.1.2** The de-icing mechanism shall be integrable with 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 de-icing 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 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.

Functional Requirement 2

FR.2 The prototype shall remove ice.

SPEC.2.1 The prototype shall remove ice in an environment with wind speed scaled via Reynolds number to the same scale as the test section size (full-scale wind speed = 65 knots indicated).

DR.2.1 The prototype 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 (7.17 in) as measured from the leading edge on the upper airfoil surface and to 2% of the chord (2.04 in) as measured from the leading edge on the lower airfoil 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 activating the prototype shall be 0.1 in.

Functional Requirement 3

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.

Housing Adhesive Strength

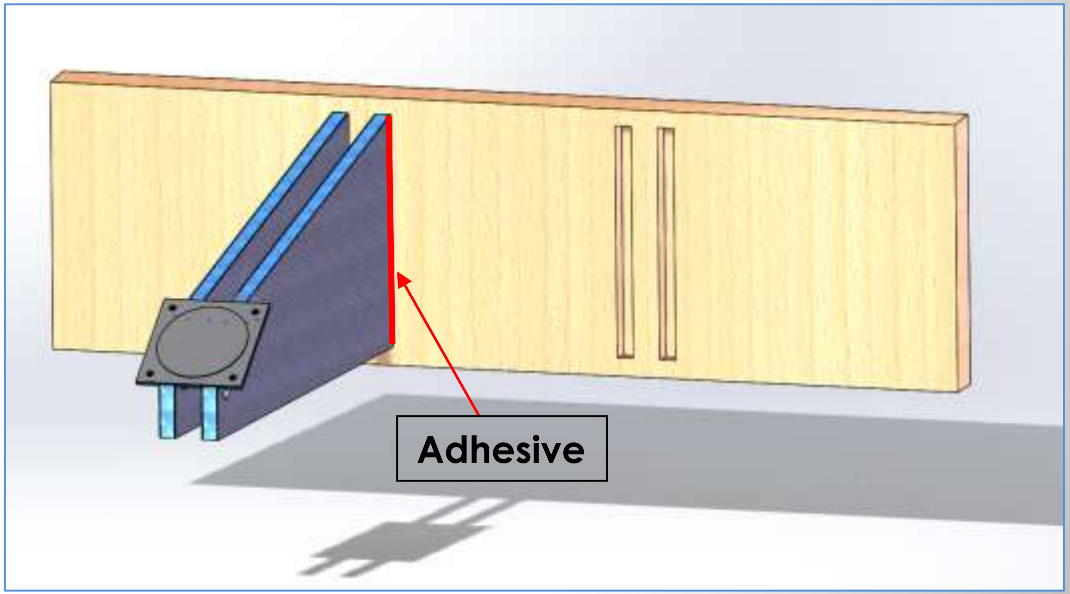
Assume total force is applied to adhesive

$$Force\ in\ adhesive = 40.5\ lb$$

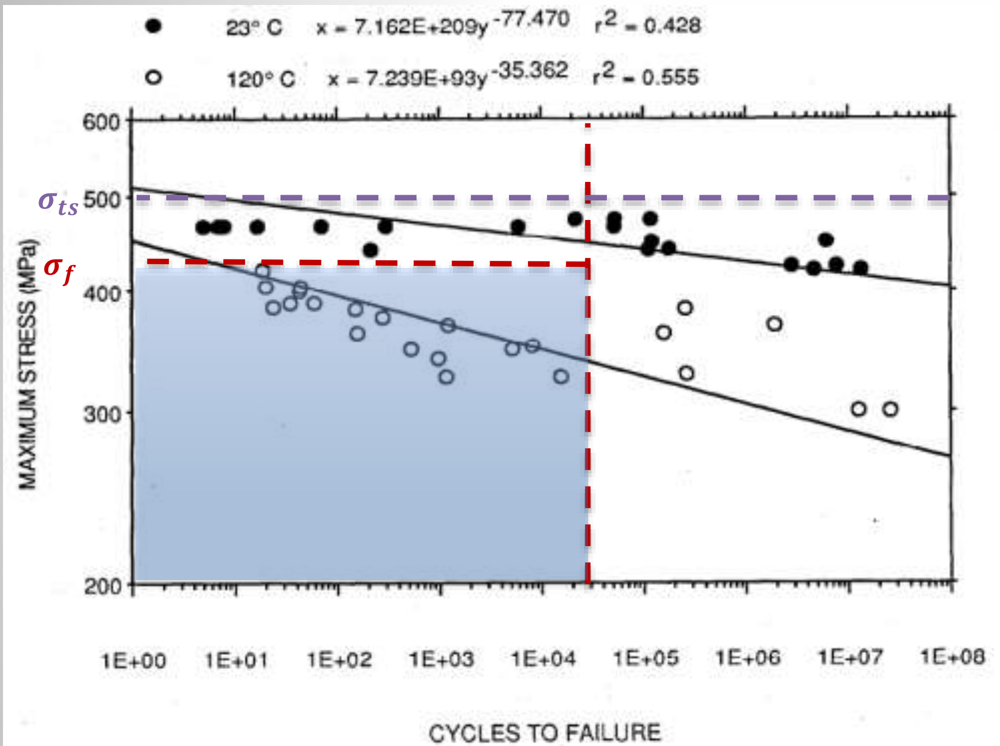
$$Area = 56\ in^2$$

$$\tau = \frac{F}{A} = \frac{40.5}{56} = 0.72\ psi$$

$$\tau_{Fail} = 218\ ksi$$



Curved Test Section – 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

✓ Actual stress amplitude is less than maximum

Flat Plate Analysis – Video

Bird's Eye View of Ice-Hammer Test

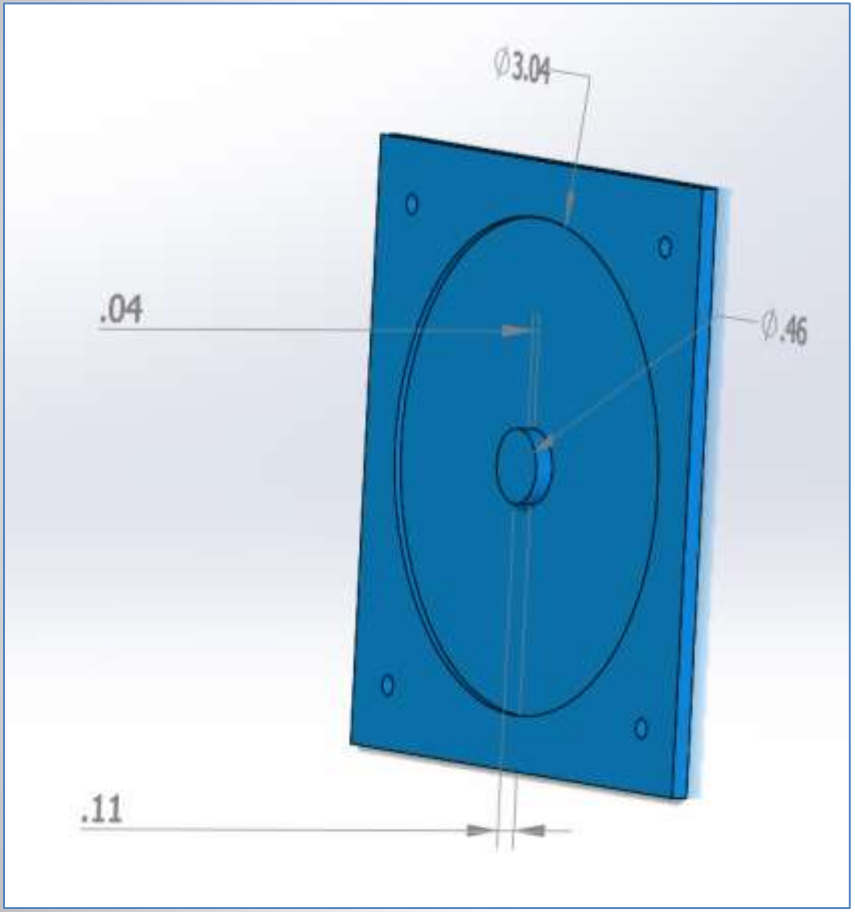
Carbon Fiber Flat Plate

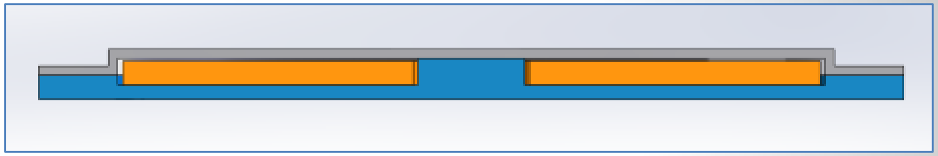
Adhered Ice

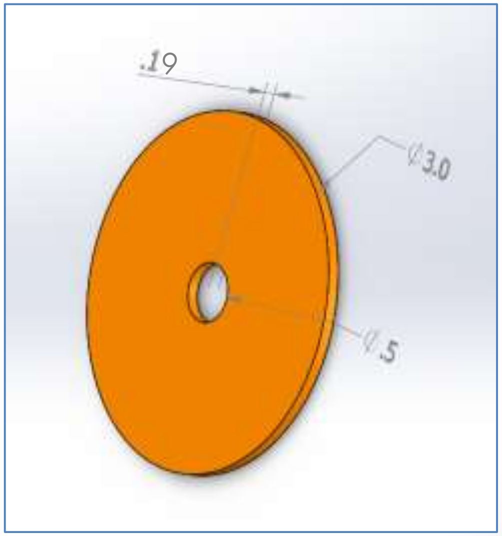
Direction of Hammer Motion

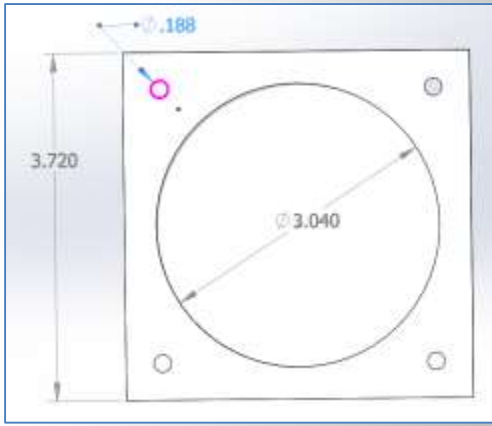
Project Description | **Design Solution** | Verification & Validation | Planning

Housing Unit Details









Flat Plate Analysis – Fracture Toughness

$$K_{1c} = y\sigma_{max}\sqrt{\pi c_{crit}}$$

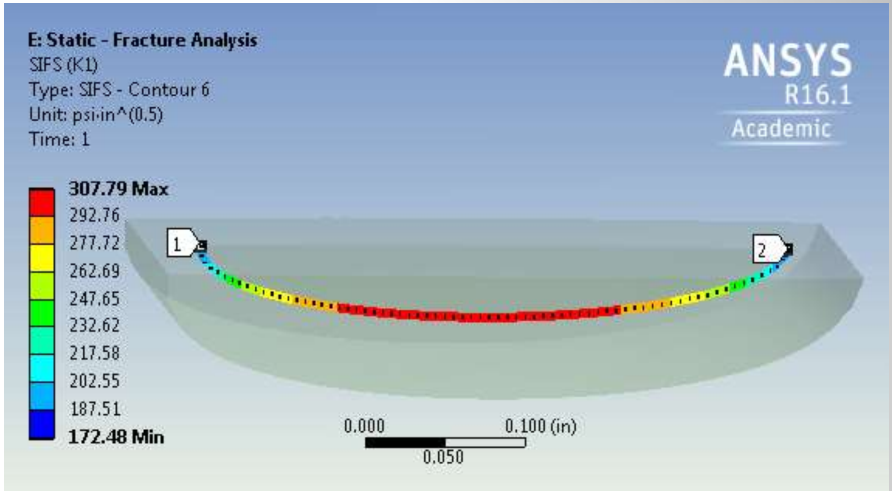
K_{1c} = fracture toughness = 0.109 $\frac{ksi}{in^{1/2}}$

y = for edge cracks = 1

σ_{max} = stress in ice = 347 psi

c_{crit} = length at which crack will propagate through material

$$c_{crit} = \frac{\left(\frac{K_{1c}}{y\sigma_{max}}\right)^2}{\pi} = \mathbf{0.03\ in}$$



$$K_{max} = 0.308\frac{ksi}{in^{1/2}} \qquad K_{1c} = 0.109\frac{ksi}{in^{1/2}}$$

$$\boldsymbol{K_{max} > K_{1c}}$$

✓ **Crack will propagate through the ice**

Project Description | **Design Solution** | Verification & Validation | Planning

Electronics Specifications

Resistors: Power thin film (PF2203)
- Can withstand 2000 V at 50 W
- Price: 5 USD

Diodes: Damper & modulation (DMV1500MFD5)
- 1500 V_{RRM} (repetitive reverse peak voltage)
- 2.2 V_F (forward voltage drop)
- Price: 1.50 USD

Power Supply (for testing): HP 6521A
- 1000 V_{DC}
- 0 – 200 mA
- Price: 260 USD

Thyristors: TO-200AB
- 2000 V_{RRM}
- Price: 70 USD

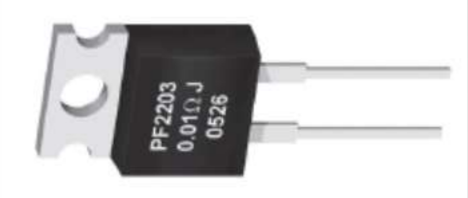


Figure #. PF2203 Resistor

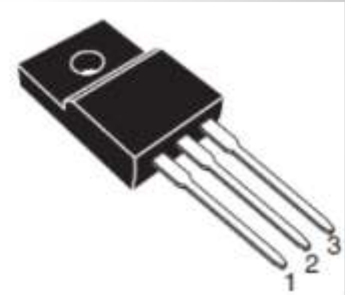


Figure #. DMV Diode

Figure #. TO-200AB Thyristor

Testing Circuit Components

HP Agilent Harrison 6521A Power Supply

- 0-1000VDC 0-200 mA
- $260.00

Kemet C44UQGQ6500F8SK Capacitor

- 500 μF 0 -1100 VDC
- 6000 A peak current
- 1.1 mΩ ESR

Electronics Specifications

Capacitor: 500 μF

- Non-polarized (safe for current back flow)
- Part: 399-5954-ND DigiKey ($140.00)

Specification	Value (in)
Diameter (D)	3.35
Height (H1)	6.93
Distance between terminals (S)	1,25
Mounting (M)	0.47x0.63

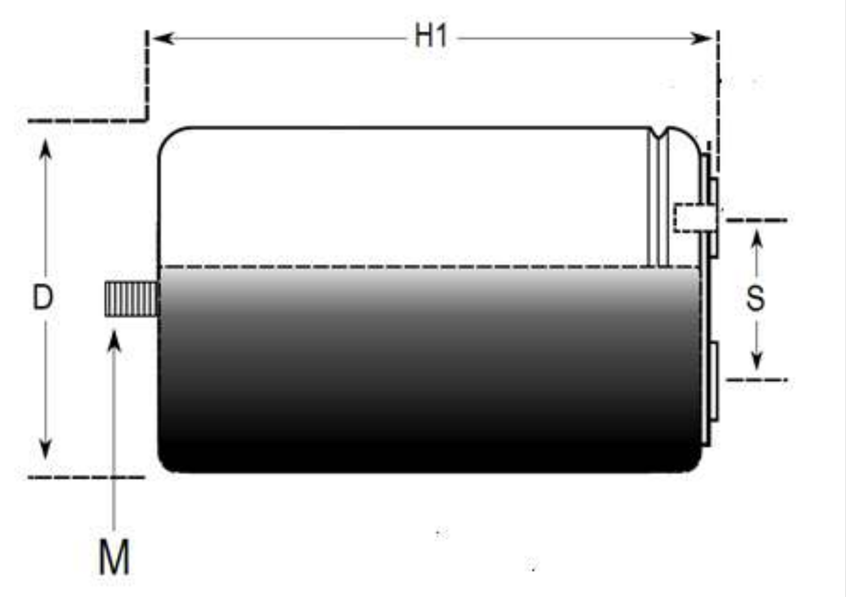


Figure ###. Capacitor dimensions from data sheet

Safety Precautions

Personal Protective Equipment

- Rubber Gloves
- Safety Glasses
- Grounded Capacitor Discharge Rod
- Long Pants
- Long Sleeves
- Closed-Toe shoes

Protective Circuitry

- Emergency Cutoff Switch
  - Cuts power from power supply
  - Grounds capacitors to discharge and prevent charging

Project Description | Design Solution | Verification & Validation | Planning

Safety Precautions

Personal Protective Standards

- Three personnel on job at all times
  - One Worker
    - Performs testing tasks
  - One Inspector
    - Reads testing checklist/procedure
    - Watches worker perform work
    - Always holds emergency cutoff switch
  - One Fire Watch
    - Gets help if situation turns dangerous
    - Stands next to fire extinguisher
- Double check that capacitors are discharged
  - Leave emergency switch tripped between tests
  - Use discharge rod and mustimeter after each test to ensure that capacitor bank is fully discharged and grounded
- Never work on system while power supply is on

Safety Precautions

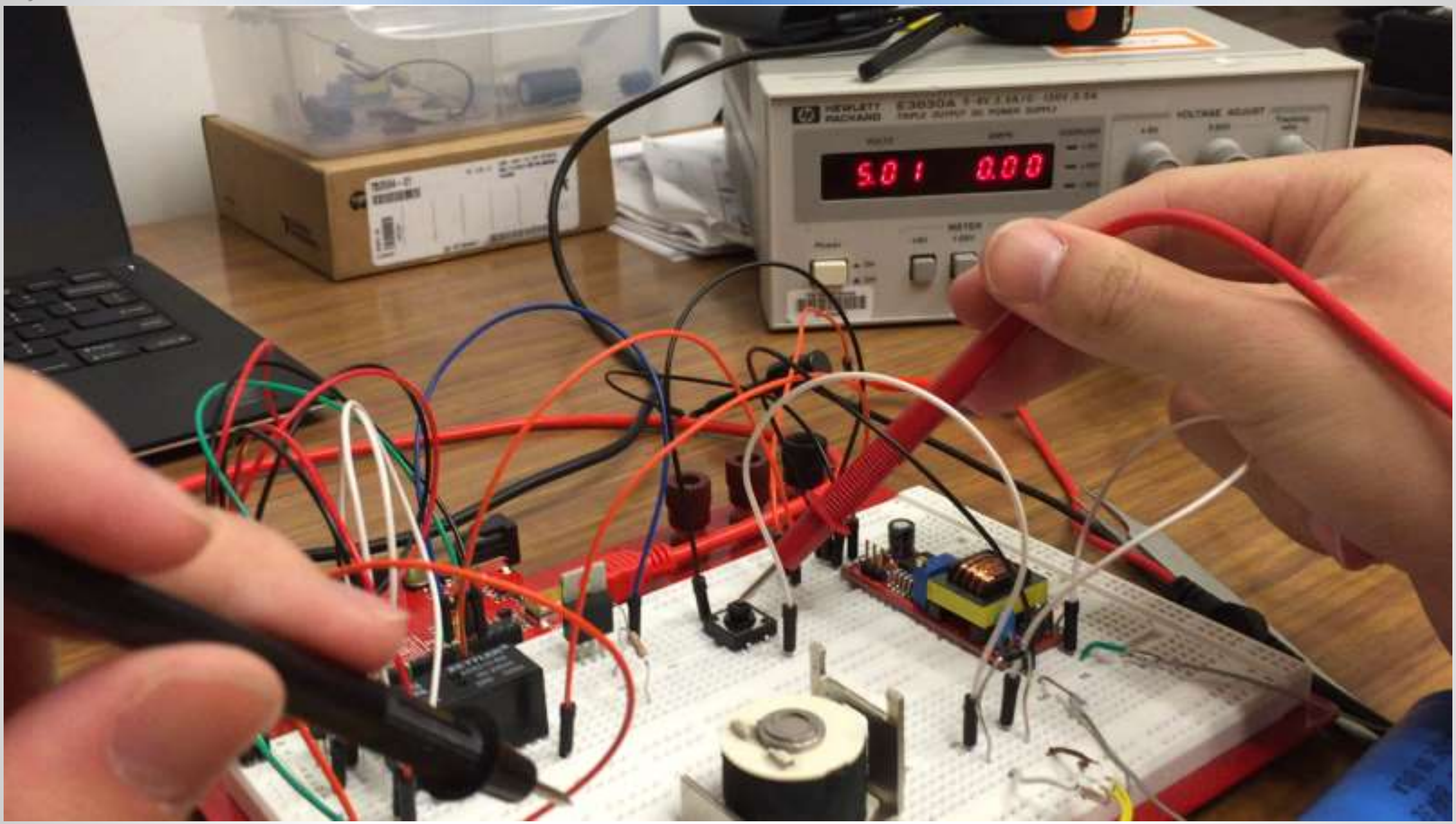
For High Voltage Circuit

- Never work alone, never assuming anything without checking
- Wear safety gloves and rubber bottom shoes
- Connect/Disconnect any test leads with the equipment unpowered and unplugged
- Understand the circuit in deep

For Laser

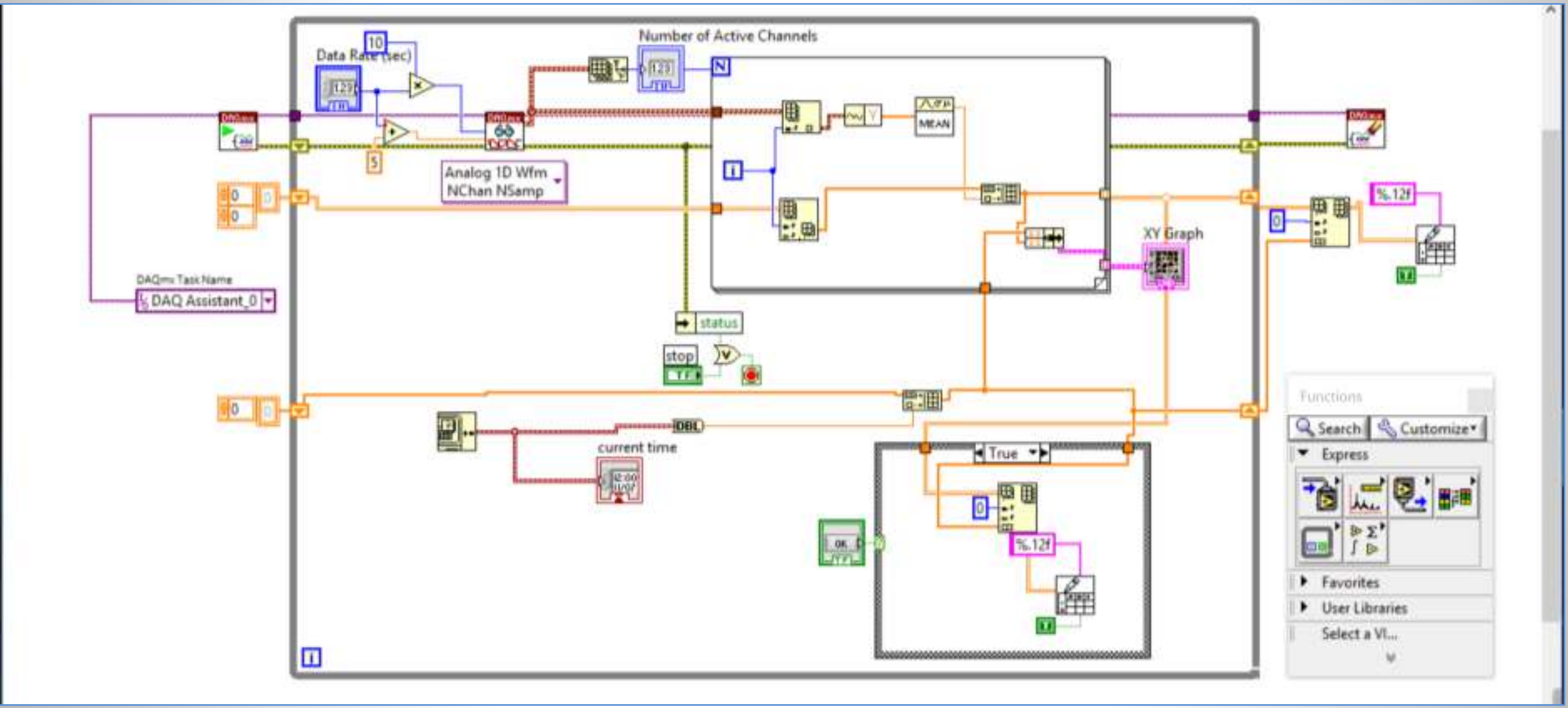
- Always work alone
- Never look directly into laser beam
- "Laser in Use" must be illuminated
- Never sit down
- Wear specific safety goggles
- Block the beam and close system shutters before turning off the laser

Solenoid Demonstration



Software

LabVIEW Code – DAQ for Thermocouples



Project Description | Design Solution | Verification & Validation | Planning

Phase Control Thyristor

PRODUCT SUMMARY	
Package	TO-200AB (A-PUK)
Diode variation	Single SCR
$I_{T(AV)}$	410 A
V_{DRM}/V_{RRM}	400 V, 800 V, 1200 V, 1400 V, 1600 V, 1800 V, 2000 V
V_{TM}	1.69 V
I_{GT}	90 mA
T_J	-40 °C to 125 °C

MAJOR RATINGS AND CHARACTERISTICS

PARAMETER	TEST CONDITIONS	VALUES	UNITS
$I_{T(AV)}$		410	A
	T_{hs}	55	°C
$I_{T(RMS)}$		780	A
	T_{hs}	25	°C
I_{TSM}	50 Hz	5700	A
	60 Hz	5970	
I^2t	50 Hz	163	kA^2s
	60 Hz	149	
V_{DRM}/V_{RRM}		400 to 2000	V
t_q	Typical	100	μs
T_J		-40 to 125	°C

ELECTRICAL SPECIFICATIONS

VOLTAGE RATINGS

TYPE NUMBER	VOLTAGE CODE	V_{DRM}/V_{RRM}, MAXIMUM REPETITIVE PEAK AND OFF-STATE VOLTAGE V	V_{RSM}, MAXIMUM NON-REPETITIVE PEAK VOLTAGE V	I_{DRM}/I_{RRM}, MAXIMUM AT T_J = T_J MAXIMUM mA
VS-ST230C..C	04	400	500	30
	08	800	900	
	12	1200	1300	
	14	1400	1500	
	16	1600	1700	
	18	1800	1900	
	20	2000	2100	

Revision: 16-Dec-13 1 Document Number: 94398

Project Description | Design Solution | Verification & Validation | Planning

Phase Control Thyristor

ABSOLUTE MAXIMUM RATINGS

PARAMETER	SYMBOL	TEST CONDITIONS			VALUES	UNITS
Maximum average on-state current at heatsink temperature	$I_{T(AV)}$	180° conduction, half sine wave double side (single side) cooled			410 (165)	A
					55 (85)	°C
Maximum RMS on-state current	$I_{T(RMS)}$	DC at 25 °C heatsink temperature double side cooled			780	A
Maximum peak, one-cycle non-repetitive surge current	I_{TSM}	t = 10 ms	No voltage reapplied	Sinusoidal half wave, initial $T_J = T_J$ maximum	5700	
		t = 8.3 ms			5970	
		t = 10 ms	100 % V_{RRM} reapplied		4800	
		t = 8.3 ms			5000	
Maximum I^2t for fusing	I^2t	t = 10 ms	No voltage reapplied		163	kA^2s
		t = 8.3 ms			148	
		t = 10 ms	100 % V_{RRM} reapplied		115	
		t = 8.3 ms			105	
Maximum $I^2\sqrt{t}$ for fusing	$I^2\sqrt{t}$	t = 0.1 to 10 ms, no voltage reapplied			1630	$kA^2\sqrt{s}$
Low level value of threshold voltage	$V_{T(TO)1}$	(16.7 % x π x $I_{T(AV)}$ < I < π x $I_{T(AV)}$), $T_J = T_J$ maximum			0.92	V
High level value of threshold voltage	$V_{T(TO)2}$	(I > π x $I_{T(AV)}$), $T_J = T_J$ maximum			0.98	
Low level value of on-state slope resistance	r_{t1}	(16.7 % x π x $I_{T(AV)}$ < I < π x $I_{T(AV)}$), $T_J = T_J$ maximum			0.88	mΩ
High level value of on-state slope resistance	r_{t2}	(I > π x $I_{T(AV)}$), $T_J = T_J$ maximum			0.81	
Maximum on-state voltage	V_{TM}	I_{pk} = 880 A, $T_J = T_J$ maximum, t_p = 10 ms sine pulse			1.69	V
Maximum holding current	I_H	T_J = 25 °C, anode supply 12 V resistive load			600	mA
Maximum (typical) latching current	I_L				1000 (300)	

SWITCHING

PARAMETER	SYMBOL	TEST CONDITIONS	VALUES	UNITS
Maximum non-repetitive rate of rise of turned-on current	dI/dt	Gate drive 20 V, 20 Ω, t_r ≤ 1 μs $T_J = T_J$ maximum, anode voltage ≤ 80 % V_{DRM}	1000	A/μs
Typical delay time	t_d	Gate current 1 A, dI_g/dt = 1 A/μs V_d = 0.67 % V_{DRM}, T_J = 25 °C	1.0	μs
Typical turn-off time	t_q	I_{TM} = 300 A, $T_J = T_J$ maximum, dI/dt = 20 A/μs, V_R = 50 V, dV/dt = 20 V/μs, gate 0 V 100 Ω, t_p = 500 μs	100	

BLOCKING

PARAMETER	SYMBOL	TEST CONDITIONS	VALUES	UNITS
Maximum critical rate of rise of off-state voltage	dV/dt	$T_J = T_J$ maximum linear to 80 % rated V_{DRM}	500	V/μs
Maximum peak reverse and off-state leakage current	I_{RRM}, I_{DRM}	$T_J = T_J$ maximum, rated V_{DRM}/V_{RRM} applied	30	mA

TRIGGERING

PARAMETER	SYMBOL	TEST CONDITIONS		VALUES TYP.	VALUES MAX.	UNITS
Maximum peak gate power	P_{GM}	$T_J = T_J$ maximum, t_p ≤ 5 ms		10.0		W
Maximum average gate power	$P_{G(AV)}$	$T_J = T_J$ maximum, f = 50 Hz, d% = 50		2.0		
Maximum peak positive gate current	I_{GM}	$T_J = T_J$ maximum, t_p ≤ 5 ms		3.0		A
Maximum peak positive gate voltage	+ V_{GM}	$T_J = T_J$ maximum, t_p ≤ 5 ms		20		V
Maximum peak negative gate voltage	- V_{GM}			5.0		
DC gate current required to trigger	I_{GT}	T_J = - 40 °C	Maximum required gate trigger/ current/voltage are the lowest value which will trigger all units 12 V anode to cathode applied	180	-	
		T_J = 25 °C		90	150	mA
		T_J = 125 °C		40	-	
DC gate voltage required to trigger	V_{GT}	T_J = - 40 °C		2.9	-	
		T_J = 25 °C		1.8	3.0	V
		T_J = 125 °C		1.2	-	
DC gate current not to trigger	I_{GD}	$T_J = T_J$ maximum	Maximum gate current/voltage not to trigger is the maximum value which will not trigger any unit with rated V_{DRM} anode to cathode applied	10		mA
DC gate voltage not to trigger	V_{GD}			0.25		V

THERMAL AND MECHANICAL SPECIFICATIONS

PARAMETER	SYMBOL	TEST CONDITIONS	VALUES	UNITS
Maximum operating temperature range	T_J		- 40 to 125	°C
Maximum storage temperature range	T_{Stg}		- 40 to 150	
Maximum thermal resistance, junction to heatsink	R_{thJ-hs}	DC operation single side cooled	0.17	K/W
		DC operation double side cooled	0.08	
Maximum thermal resistance, case to heatsink	R_{thC-hs}	DC operation single side cooled	0.033	
		DC operation double side cooled	0.017	
Mounting force, ± 10 %			4900 (500)	N (kg)
Approximate weight			50	g
Case style		See dimensions - link at the end of datasheet	TO-200AB (A-PUK)	

ΔR_{thJC} CONDUCTION

CONDUCTION ANGLE	SINUSOIDAL CONDUCTION		RECTANGULAR CONDUCTION		TEST CONDITIONS	UNITS
	SINGLE SIDE	DOUBLE SIDE	SINGLE SIDE	DOUBLE SIDE		
180°	0.015	0.017	0.011	0.011	$T_J = T_J$ maximum	K/W
120°	0.018	0.019	0.019	0.019		
90°	0.024	0.024	0.026	0.026		
60°	0.035	0.035	0.036	0.036		
30°	0.060	0.060	0.060	0.061		

Project Description | **Design Solution** | Verification & Validation | Planning

Power Supply

INPUT:
115Vac ±10%, 48-440Hz, 4A, 270W.

OUTPUT:
0-1000 Vdc, 0-200 mA.

LOAD REGULATION:
Constant Voltage: Less than 0.005% or 20mV, whichever is greater, for a full load to no load change in output current.

Constant Current: Less than 2% or 1mA, whichever is greater, for a full load to no load change in output current.

LINE REGULATION:
For a change in line voltage of 115Vac ±10% at any output voltage and current within rating.

Constant Voltage: Less than 0.005% or 20mV, whichever is greater.
Constant Current: Less than 1 mA.

PARD (RIPPLE AND NOISE):
At any line voltage and under any load condition within rating
Constant Voltage: Less than 1mV rms/150mV p-p.
Constant Current: Less than 2 mA rms.

TRANSIENT RECOVERY TIME:
Less than 50 μsec is required for output voltage recovery to within 0.005% or 20 mV, whichever is greater, following a full load to no load or no load to full load change in output current.

TEMPERATURE RATINGS:
Operating: 0 to 55°C Storage: - to +75°C.

TEMPERATURE COEFFICIENT:
Output change per degree centigrade change in ambient following 60 minutes warm-up
Constant Voltage: 0.012% plus 1mV.
Constant Current: 0.2% plus 0.2mA.

STABILITY:
Under constant ambient conditions, total drift for 8 hours following 60 minutes warm-up
Constant Voltage: 0.036% plus 3 mV.
Constant Current: 0.25% plus 0.5 mA.

CONTROLS:
Voltage controls consist of a three decade thumbwheel switch plus a thumbwheel vernier with 0.002% resolution. A single turn potentiometer controls output current.

METERS:
Zero to 1 kV and 0-200 mA front panel meters are included. They provide accuracy of 2% full scale.

CALIBRATION ACCURACY:
One percent of the voltage control setting, +1V.

OUTPUT IMPEDANCE:

DC to 100 Hz (cps.)	--	less than 0.01Ω.
100 Hz to 1 k Hz	--	less than 0.02Ω.
1 k Hz to 100 k Hz	--	less than 0.5Ω.
100 k Hz to 1 M Hz	--	less than 3Ω.

SIZE:
$5\frac{1}{4}$" H x 18" D x 19" W (standard rack width).

WEIGHT:
42lbs. net, 63lbs. shipping.

FINISH:
Light gray front panel with dark gray case.

Project Description | **Design Solution** | Verification & Validation | Planning

Capacitor: C44U Series
700 – 1300 VDC

General Technical Data

Dielectric	Polypropylene Metallized Film – non inductive self-healing
Application	DC Filtering/DC Link
Climatic Category	40/85/21 IEC 60068–1
Maximum Operating Temperature	+90°C
Upper Temperature T_{MAX} Group A	+85°C IEC 61071 – Endurance Test Temperature
Upper Temperature T_{MAX} Group B	+70°C IEC 61071 – Endurance Test Temperature
Lower Temperature T_{min}	-40°C
Standard	IEC 61071
Protection	Aluminium case with or without, threaded bolt M12
	Plastic deck flame retardant execution UL 94 V–0
	Thermosetting resin sealing UL 94 V–0 compliant
Installation	Any position
Leads	High current M6 or M8 terminals
Packaging	Packed in cardboard boxes with protection for the terminals
RoHS Compliant	Compliant with the restricted substance requirements of Directive 2002/95/EC

Electrical Characteristics

Capacitance Tolerance	±10% at +25°C
Dissipation Factor (DF)	≤ 0.0002 at 10 kHz with T = 25°C ±5°C
Surge Voltage	1.5 x V_{NDC} for maximum 10 times in lifetime at +25°C
Over-Voltage (IEC 61071)	1.15 x V_{NDC} for maximum 30 minimum, once per day
	1.3 x V_{NDC} for maximum 1 minimum, once per day
Peak Non-Repetitive Current	1.5 x I_{pk} maximum 1,000 times in lifetime
Insulation Resistance	IR x C ≥ 30,000 seconds at 100 VDC 1 minute at +25°C
Capacitance Deviation in Operation	±1.5% maximum on capacitance value measured at +25°C
Permissible Relative Humidity	Annual average ≤ 70%; 85% on 30 days/year randomly distributed throughout the year. Dewing not admissible.

Life Expectancy

Life Expectancy – Group A	100,000 hours at V_{NDC} @ Hot-Spot temperature T_{HS} = 85°C
Life Expectancy – Group B	100,000 hours at V_{NDC} @ Hot-Spot temperature T_{HS} = 70°C
Capacitance drop at end of life	-10% (typical)
Failure Rate IEC 61709	50 FIT at V_{NDC} @ reference T_{HS} (see FIT curves)

Test Method

Test voltage between terminals	1.5 x V_{NDC} for 10 seconds or 1.65 V_{NDC} for 2 seconds at 25°C
Test voltage between terminals and case	3.2 kVAC 50 Hz for 2 seconds
Damp Heat	IEC 60068-2-78
Change of temperature	IEC 60068-2-14

500W Resistor PF2200

Specification	Value	
Temperature Range	-55°C to +155°C : PF2202, PF2203, PF2205	
Dielectric Strength	2000 VAC	
Max. Operating Voltage	$\sqrt{P*R}$ (500V MAX)	
Insulation Resistance	>1000 Meg-Ohm	
Inductance	PF2202 / PF2203 8.38 nH, PF2205 9.65 nH	
Environmental Performance	**ΔR**	**Test Conditions**
Load Life	±1%	25°C, 90 min ON, 30 min OFF, 1000 hr
Humidity Resistance	±1%	40°C, 90-95% RH, DC 0.1W, 1000 hr
Temperature Cycle	±0.25%	-55°C for 30 min, +155°C for 30 min, 5 cycles
Solder Heat	±0.1%	+350 / -5°C 3s
Vibration	±0.25%	IEC60068-2-6

Diode DMV1500M

Table 1: Main Product Characteristics

	DAMPER	MODUL.
$I_{F(AV)}$	6 A	3 A
V_{RRM}	1500 V	600 V
t_{rr} (max)	135 ns	50 ns
V_F (max)	1.65V	1.4 V

Table 2: Order Codes

Part Number	Marking
DMV1500MFD	DMV1500M
DMV1500MFD5	DMV1500M

Table 3: Absolute Maximum Ratings

Symbol	Parameter		Value		Unit
			Damper	Modul.	
V_{RRM}	Repetitive peak reverse voltage		1500	600	V
I_{FSM}	Surge non repetitive forward current	tp = 10ms sinusoidal	75	35	A
T_{stg}	Storage temperature range		-40 to +150		°C
T_j	Maximum operating junction temperature		150		°C

Table 4: Thermal Resistance

Symbol	Parameter	Value	Unit
$R_{th(j-c)}$	Junction to case thermal resistance	3.7	°C/W

Table 5: Static Electrical Characteristics

Symbol	Parameter	Test conditions		Value T_j = 25°C		Value T_j = 125°C		Unit
				Typ.	Max.	Typ.	Max.	
I_R *	Reverse leakage current	Damper	V_R = 1500 V		100	100	1000	µA
		Modulation	V_R = 600 V		20	3	50	
V_F **	Forward voltage drop	Damper	I_F = 6 A	1.4	2.2	1.2	1.65	V
		Modulation	I_F = 3 A		1.8	1.1	1.4	

Pulse test: * tp = 5 ms, δ < 2%
** tp = 380 µs, δ < 2%

To evaluate the maximum conduction losses of the **DAMPER** and **MODULATION** diodes use the following equations :

DAMPER: $P = 1.37 \times I_{F(AV)} + 0.047 \times I_{F}^{2}{}_{(RMS)}$

MODULATION: $P = 1.12 \times I_{F(AV)} + 0.092 \times I_{F}^{2}{}_{(RMS)}$

Table 6: Recovery Characteristics

Symbol	Parameter	Test conditions		Value Damper		Value Modul.		Unit
				Typ.	Max.	Typ.	Max.	
t_{rr}	Reverse recovery time	I_F = 100mA, I_R =100mA, I_{RR} = 10mA	T_j = 25°C	750		110	350	ns
		I_F = 1A, dI_F/dt = -50 A/µs, V_R =30V	T_j = 25°C	110	135	35	50	

Project Description | Design Solution | Verification & Validation | Planning

High Wind Speed Test - Sensors

Testing Needs:

Temperature Range

- Room temperature: Below 0˚C
- Wing Test Section: Expected to be no higher than XX˚C

Recording

- Need to be able to perform frame by frame analysis
- High accuracy

Measuring Amperage

- Amperage should remain at or below the ADD VALUE.

Testing Speed

- Free stream velocity must be 65 KIAS.

Selected Sensors:

T-Type Thermocouples

- Range: -200˚C to 200˚C
- **Measure temperature inside of the wing test section and room temperature.**

High Speed Camera

- 60 FPS
- **Record testing and use the frames to verify the deflection of the carbon fiber.**

Ammeter

- TYPE
- WHAT can it measure
- **Will measure amps in the circuit**

Anemometer

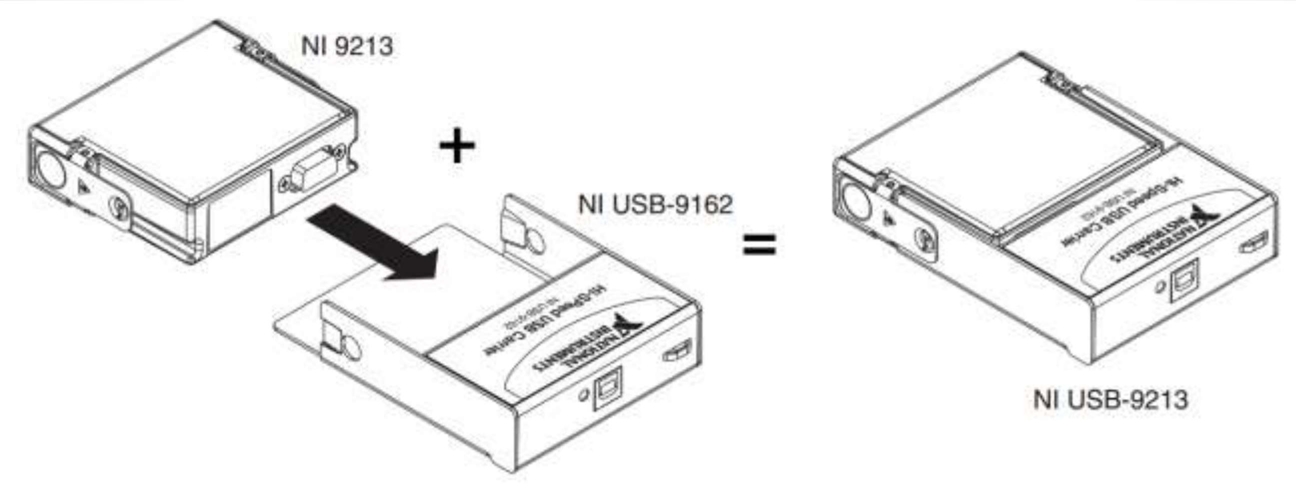
- Available on campus
- **Used to measure wind speed near the leading edge.**

Project Description | Design Solution | **Verification & Validation** | Planning

Fan Specifications

- Diameter: 42 inches
- Price:$300
- Volumetric Flow Rate
  - Max: 17,600 CFM
  - Min: 13,200 CFM

Temperature DAQ



- 16 differential channels
- Operating Temperature of -40˚C to 70˚C
- Sample rate: $\frac{75\ Samples}{second}$

Project Description | Design Solution | **Verification & Validation** | Planning

High Wind Speed Test - Process

Initial Measure-ments
- Measure the wind speed at the leading edge of the wing section.
- Take initial temperatures of the environment.
- Measure the ice thickness on wing section.

Set-Up
- Remove wing test section from the trough.
- Place the wing section inside the wind tunnel.
- Clamp the test section to the table to secure it down.
- Place the thermocouples in the indicated places.
- Connect electronics to the mechanism

Test
- Ensure that everyone is inside of the ITLL.
- Begin collecting temperature data.
- Activate the system.
- Power off.

Measure
- Measure ice thickness after actuation of the system.
- Measure the wind speed at the leading edge.

Clean up
- Save data
- Clean all ice that was shed.
- Put away all of the equipment.
- Set up the trough to re-freeze.

Laser Specifications

Laser Detector
Thorlabs S302C
- Thermal Power Sensor
- 0.19 – 25 μm
- Sensitivity of 315.82mV/W

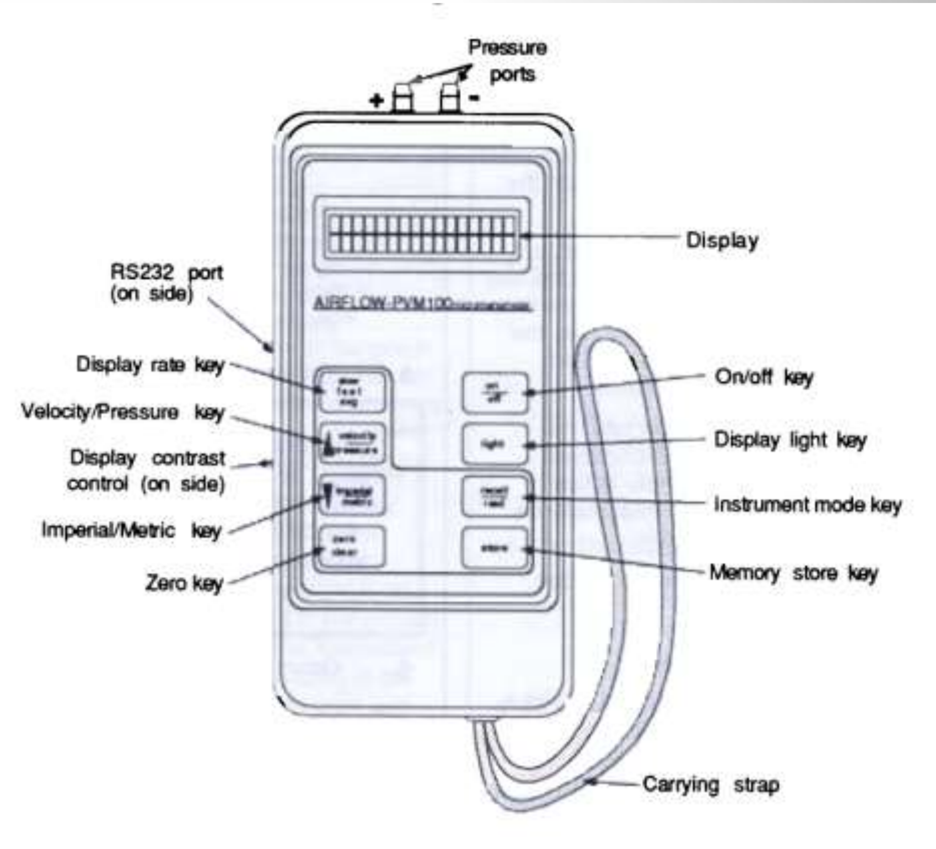
Laser
Low Frequency
- Laser Pointer

High Frequency
- Coherent DPSS 532 Lase, 500mW

INSERT PICTURE FROM RUNNAN

Micromanometer

PVM100 Micromanometer
- Velocity Range: 0 – 76 m/s
- Operating Temperature: -5˚C to +50˚C
- Resolution: 1Pa

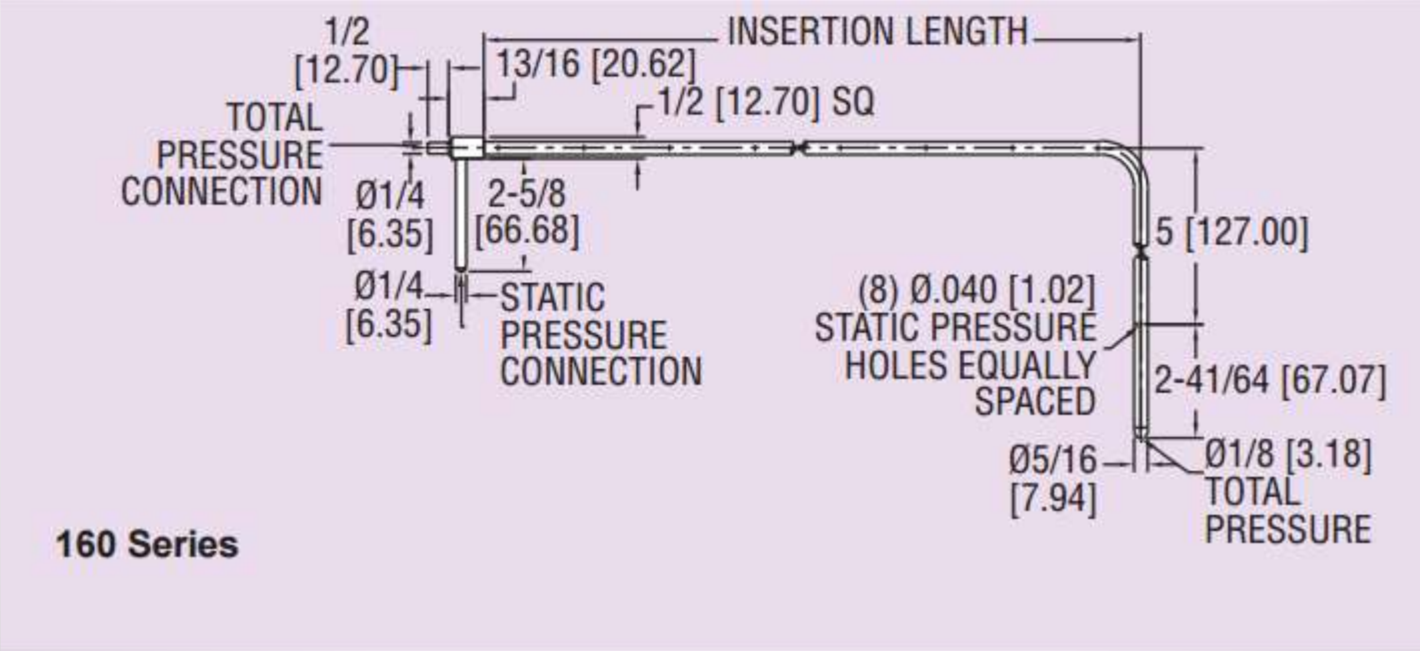


Project Description | Design Solution | Verification & Validation | Planning

Pitot Tube Probe

Dwyer 160-18 Stainless Steel Pitot Tube

- Length: 18"
- Diameter: 5/16"
- No calibration needed



Project Description | Design Solution | **Verification & Validation** | Planning

Laser Specifications

Laser Detector

Thorlabs S302C

- Thermal Power Sensor
- 0.19 – 25 μm
- Sensitivity of 315.82mV/W

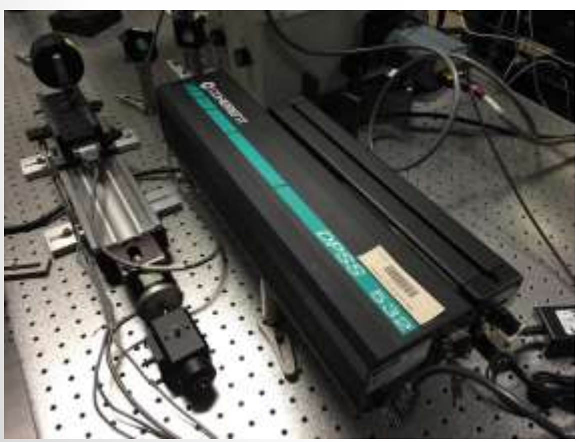
Laser

Low Frequency

- Laser Pointer

High Frequency

- Coherent DPSS 532 Lase, 500mW

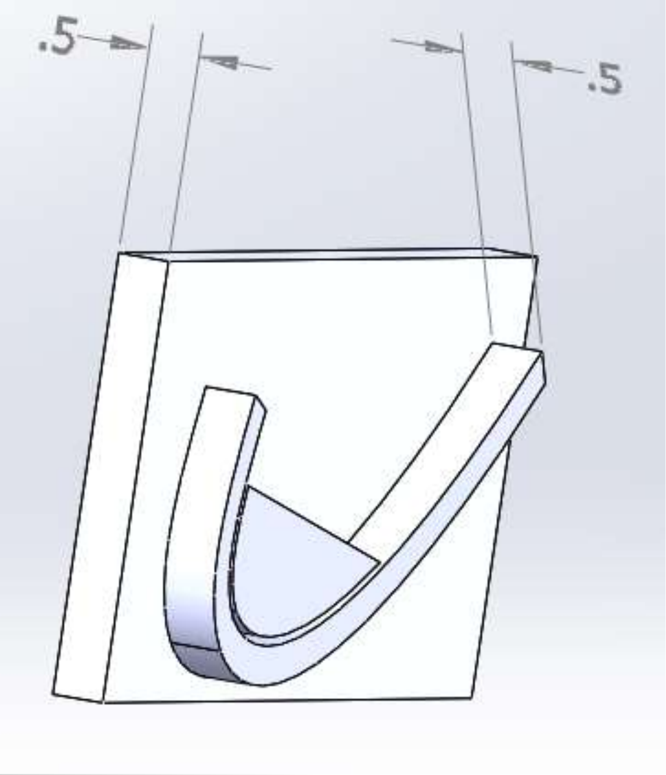


T-Type Thermocouples

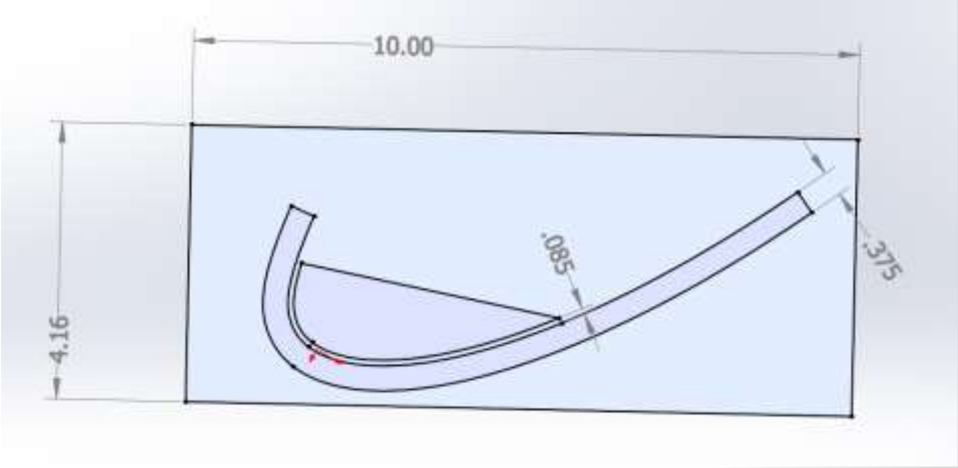
- Self-Adhesive backing for easy installation
- Response Time: <0.3 Seconds
- Length: 1 meter

Project Description | Design Solution | **Verification & Validation** | Planning

End Caps



Isometric View

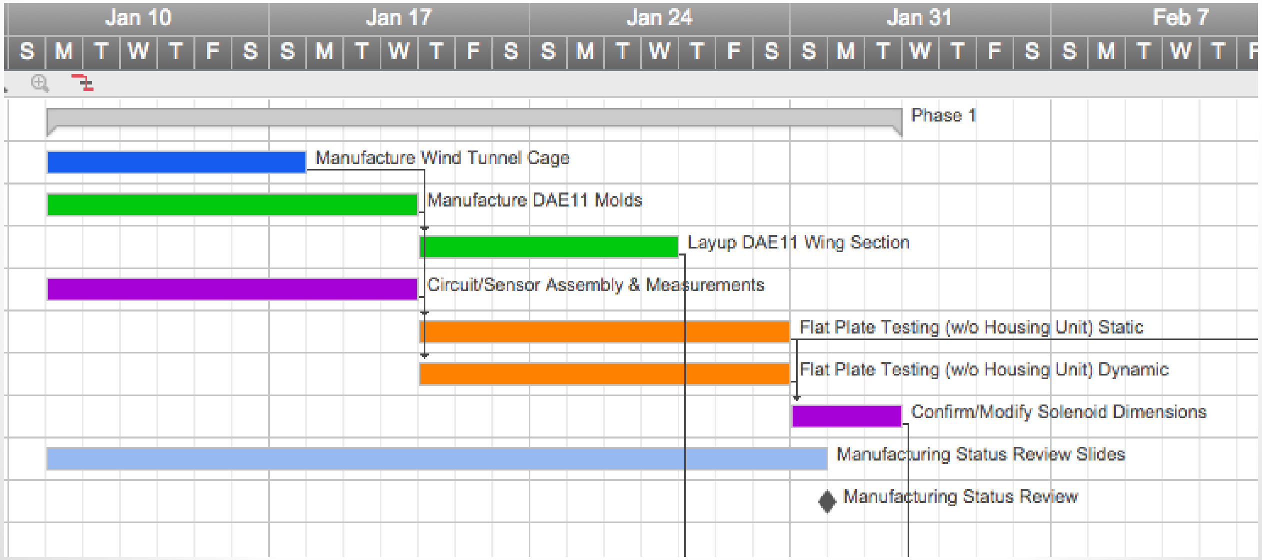


Front View

Project Description | Design Solution | **Verification & Validation** | Planning

Gantt Backup Phase 1

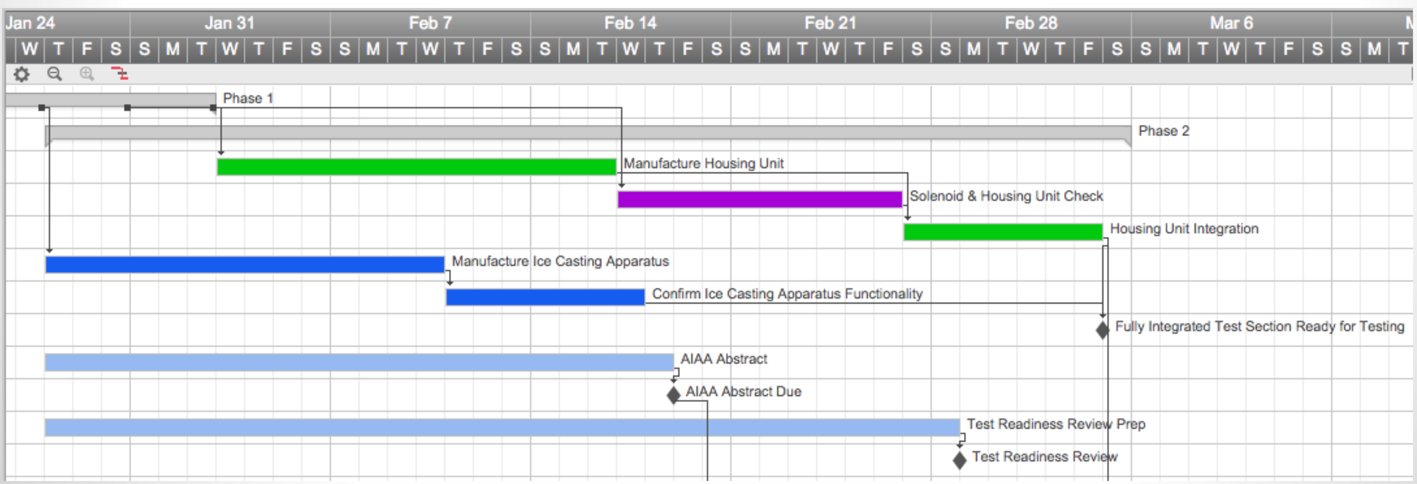
Phase 1	01/11/16	02/02/16 23d		
Manufacture Wind Tunnel Cage	01/11/16	01/17/16 7d		Testing Equipment
Manufacture DAE11 Molds	01/11/16	01/20/16 10d		Test Section
Layup DAE11 Wing Section	01/21/16	01/27/16 7d	3	Test Section
Circuit/Sensor Assembly & Measurements	01/11/16	01/20/16 10d		Solenoid/Circuit
Flat Plate Testing (w/o Housing Unit) Static	01/21/16	01/30/16 10d	5	Testing
Flat Plate Testing (w/o Housing Unit) Dynamic	01/21/16	01/30/16 10d	2, 5	Testing
Confirm/Modify Solenoid Dimensions	01/31/16	02/02/16 3d	6, 7	Solenoid/Circuit
Manufacturing Status Review Slides	01/11/16	01/31/16 21d		Class Deliverable
Manufacturing Status Review	02/01/16	02/01/16 ~0		



Project Description | Design Solution | Verification & Validation | **Planning**

Gantt Backup Phase 2

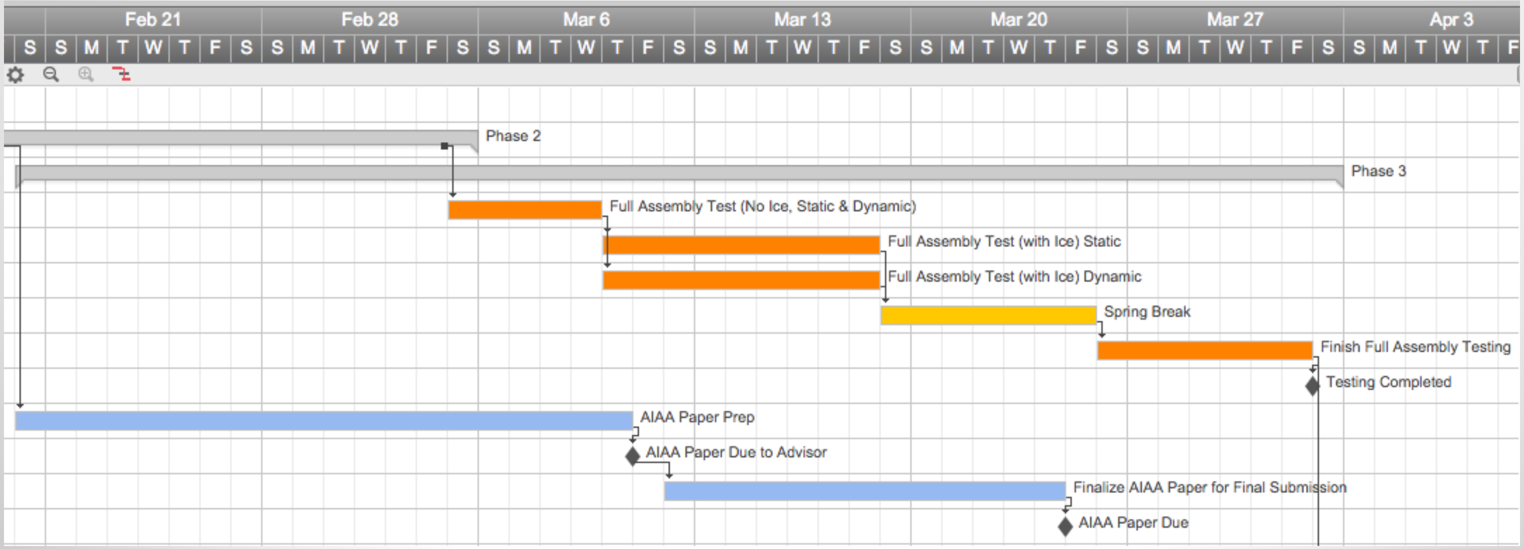
Phase 2	01/28/16	03/05/16	38d		
Manufacture Housing Unit	02/03/16	02/16/16	14d	8	Test Section
Solenoid & Housing Unit Check	02/17/16	02/26/16	10d	13, 6	Solenoid/Circuit
Housing Unit Integration	02/27/16	03/04/16	7d	13, 14	Test Section
Manufacture Ice Casting Apparatus	01/28/16	02/10/16	14d	4	Testing Equipment
Confirm Ice Casting Apparatus Functionality	02/11/16	02/17/16	7d	16	Testing Equipment
Fully Integrated Test Section Ready for Testing	03/05/16	03/05/16	~0	15, 17	
AIAA Abstract	01/28/16	02/18/16	22d		Class Deliverable
AIAA Abstract Due	02/19/16	02/19/16	~0	19	
Test Readiness Review Prep	01/28/16	02/28/16	32d		Class Deliverable
Test Readiness Review	02/29/16	02/29/16	~0	21	



Project Description | Design Solution | Verification & Validation | **Planning**

Gantt Backup Phase 3

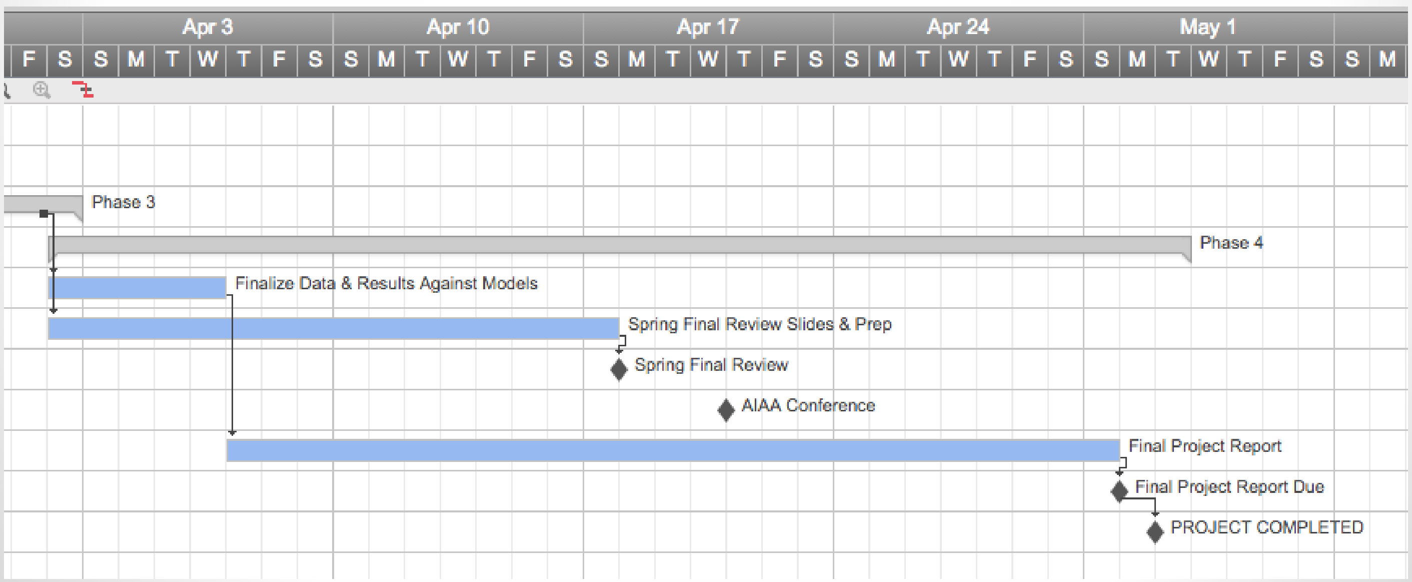
Phase 3	02/20/16	04/02/16 43d		
Full Assembly Test (No Ice, Static & Dynamic)	03/05/16	03/09/16 5d	15	Testing
Full Assembly Test (with Ice) Static	03/10/16	03/18/16 9d	25	Testing
Full Assembly Test (with Ice) Dynamic	03/10/16	03/18/16 9d	25	Testing
Spring Break	03/19/16	03/25/16 7d	26, 27	
Finish Full Assembly Testing	03/26/16	04/01/16 7d	28	Testing
Testing Completed	04/02/16	04/02/16 ~0	29	
AIAA Paper Prep	02/20/16	03/10/16 20d	20	Class Deliverable
AIAA Paper Due to Advisor	03/11/16	03/11/16 ~0	31	
Finalize AIAA Paper for Final Submission	03/12/16	03/24/16 13d	32	Class Deliverable
AIAA Paper Due	03/25/16	03/25/16 ~0	33	



Project Description | Design Solution | Verification & Validation | **Planning**

Gantt Backup Phase 4

Phase 4	04/02/16	05/03/16 32d		
Finalize Data & Results Against Models	04/02/16	04/06/16 5d	29	Class Deliverable
Spring Final Review Slides & Prep	04/02/16	04/17/16 16d	29	Class Deliverable
Spring Final Review	04/18/16	04/18/16 ~0	38	
AIAA Conference	04/21/16	04/21/16 ~0		
Final Project Report	04/07/16	05/01/16 25d	37	Class Deliverable
Final Project Report Due	05/02/16	05/02/16 ~0	41	
PROJECT COMPLETED	05/03/16	05/03/16 ~0	42	



Cost Backup

Project Manager							SOURCE
Date	Purchase	Quantity	Unit Price	Total	Ordered		
11/18/2015	Gantt Chart	6	15	90			
Manufacturing							
Date	Purchase	Quantity	Unit Price	Total	Ordered		
11/18/2015	Low Density Polyeth	1	7.25	7.25			http://www.tapplastics.com/product/plastics/plastic_sheets_rolls/ldpe_sheets/410
11/18/2015	Acrylic Sheet	1	45.76	45.76			http://www.onlinemetals.com/merchant.cfm?pid=21806&step=4&id=1586&gclid=CL6K4Zm4m8kCFZOBaQodEkwKCA
11/18/2015	Aluminum Block	1	66.36	66.36			https://www.metalsdepot.com/products/alum2.phtml?page=flat&LimAcc=%20&aident=
11/18/2015	11 oz mold release v	1	16	16			http://www.jegs.com/i/Meguiar's/538/M0811/10002/-1?CAWELAID=230006180002770392&CAGPSPN=pla&catargetid=
11/18/2015	Nomex honeycomb	1	120	120			http://www.fibreglast.com/product/Nomex_Honeycomb_1562/Vacuum_Bagging_Sandwich_Core
11/18/2015	Foam for Molds	1	2	2			
11/18/2015	1 Peel Ply Roll	1	13.45	13.45			http://www.fibreglast.com/product/Nylon_Released_Peel_Ply_582/Vacuum_Bagging_Films_Peel_Ply_Tapes
11/18/2015	Quick Lock Seals	2	36	72			https://www.acpsales.com/Quick-Locks.html
11/18/2015	Copper Sheet Metal	1	17	17			http://www.amazon.com/Copper-Sheet-Metal-12/dp/B00AKMNNX4
11/18/2015	Fan	1	300	300			http://www.globalindustrial.com/p/hvac/fans/blower/global-42-portable-blower-fan-belt-drive-600554
11/18/2015	Plywood	3	11.97	35.91			http://www.homedepot.com/s/plywood?NCNI-5
11/18/2015	2 x 4 x 96	10	2.48	24.8			http://www.homedepot.com/s/2+by+4+wood?NCNI-5
11/20/2015	Carbon Fiber PrePre	0	34.6	0			https://www.rockwestcomposites.com/cart
11/22/2015	Self-Adhesive Therr	2	64	128			http://www.omega.com/pptst/SA1.html
11/22/2015	Pitot Tube	1	75	75			http://www.qualityinstruments-direct.com/product/dwyer-160-18-pitot-tube-velometer-18-inches
11/29/2015	3M Scotch -Weld Ep	1	52.5	52.5			https://dragonplate.com/ecart/cartView.asp?rp=product%2Easp%3FpID%3D699
11/29/2015	LDPE Sheet	1	24.51	24.51			http://www.usplastic.com/catalog/item.aspx?itemid=34431&catid=705
			Total	1000.54			
Electronics							
Date	Purchase	Quantity	Unit Price	Total	Ordered		
11/18/2015	Power Supply	1	200	200			
11/19/2015	Ribbon Wire	100	1.5	150			
11/19/2015	Ribbon Wirte	100	1.5	150			
11/20/2015	Shipping Costs Wire	1	60	60			
11/20/2015	Diode Damper and s	1	36.86	36.86			NEED TO SUBMIT FOR REIMBURSEMENT FOR KELLY
11/20/2015	Digi Key Order	1	276.19	276.19			Digikey invoice 51564671
11/25/2015	Home Depot	1	18.02	18.02			Home depot receipt (Space Vinyl, 14 -2AWG Alum, PVC coated gloves, electrical tape)
11/29/2015	ELECTRONICS MARG	1	1000	1000			
			Total	1891.07			
				Total	3982.15		

Project Description | Design Solution | Verification & Validation | **Planning**

Cost Backup Sources

https://dragonplate.com/ecart/cartView.asp?rp=product%2Easp%3FpID%3D699
http://www.usplastic.com/catalog/item.aspx?itemid=34431&catid=705
http://www.omega.com/pptst/SA1.html
http://www.qualityinstruments-direct.com/product/dwyer-160-18-pitot-tube-velometer-18-inches
http://www.thorlabs.us/newgrouppage9.cfm?objectgroup_id=3333&pn=S302C
https://www.coherent.com/products/?765
http://www.tapplastics.com/product/plastics/plastic_sheets_rolls/ldpe_sheets/410
http://www.onlinemetals.com/merchant.cfm?pid=21806&step=4&id=1586&gclid=CL6K4Zm4m8kCFZOBaQodEkwKCA
https://www.metalsdepot.com/products/alum2.phtml?page=flat&LimAcc=%20&aident=
http://www.jegs.com/i/Meguiar's/538/M0811/10002/-1?CAWELAID=230006180002770392&CAGPSPN=pla&catargetid=230006180000848433&cadevice=c&gclid=CI2i5MbAm8kCFQ6maQodDvAMyw
http://www.fibreglast.com/product/Nomex_Honeycomb_1562/Vacuum_Bagging_Sandwich_Core
http://www.fibreglast.com/product/Nylon_Released_Peel_Ply_582/Vacuum_Bagging_Films_Peel_Ply_Tapes
https://www.acpsales.com/Quick-Locks.html
http://www.amazon.com/Copper-Sheet-Metal-12/dp/B00AKMNNX4
http://www.globalindustrial.com/p/hvac/fans/blower/global-42-portable-blower-fan-belt-drive-600554
http://www.homedepot.com/s/plywood?NCNI-5
http://www.homedepot.com/s/2+by+4+wood?NCNI-5
https://www.rockwestcomposites.com/cart
http://www.usplastic.com/catalog/item.aspx?itemid=34431&catid=705