Aerospace Engineering

Aurora FLIGHT SCIENCES

AESIR

University of Colorado at Boulder

Actuated Electromagnetic System for Ice Removal

Spring Final Review
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Project Purpose/Objectives

Project Background

Problem: Ice buildup on aircraft wings in flight
- Decreases Lift-to-Drag Ratio (L/D)
- Reduces mission capabilities
- In extreme cases can result in a crash

Ice formation on wing.[1]

Orion UAV [2]

Application: ORION Aircraft
- 5 day endurance
- 132 ft. wing span
- Cruising altitude of 20,000-30,000 ft. at 65 kias

Requires: Low mass, low power deicing system to increase flight path possibilities without decreasing capabilities

Problem Statement & Objectives

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

Orion UAV[2]

Functional Requirements

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

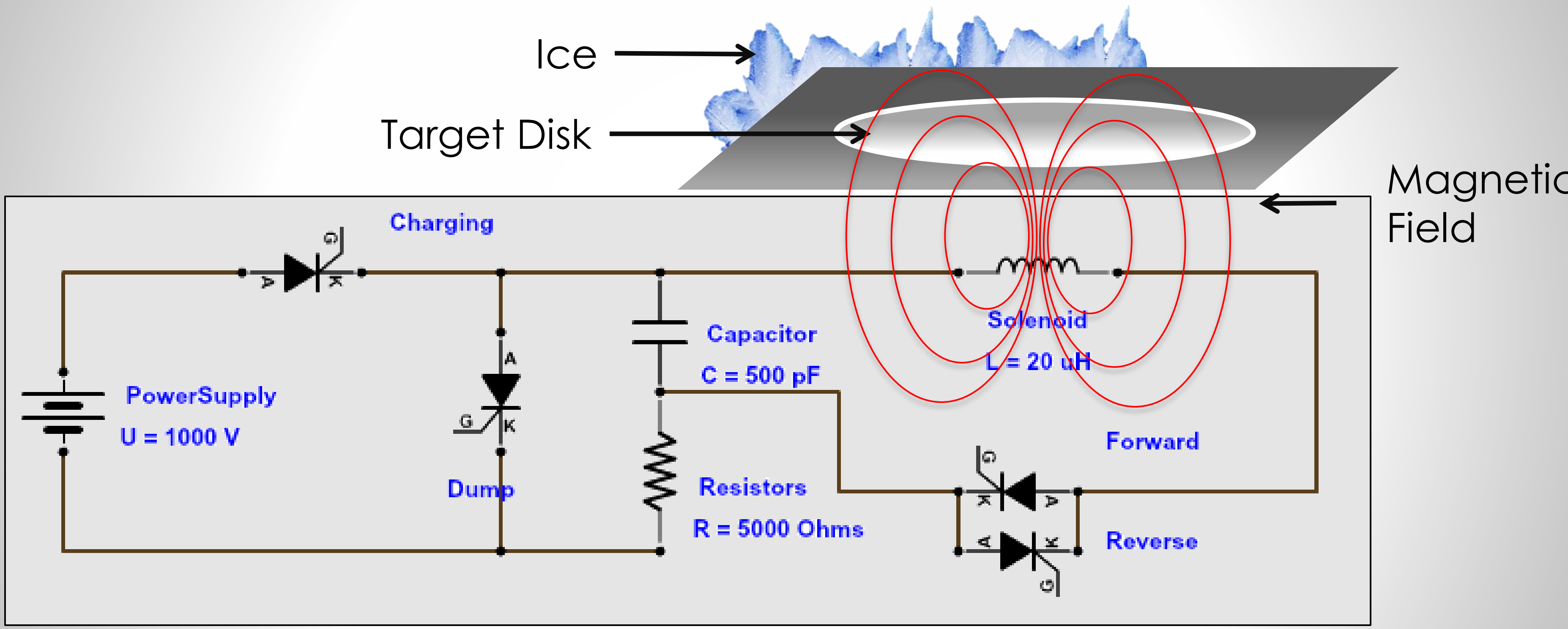
FR.2 - The prototype shall **remove ice**.

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

Design Description

Design Overview (Principle)

Electromagnetic Deicing Mechanism



Capacitor Discharge → EM Force → Deflection → Breaking Ice

Design Overview (Integration)

Solenoid Properties

- 3 inch diameter solenoid
- 60 turns
- 7 mm gap distance
- 3 inch diameter copper target disk

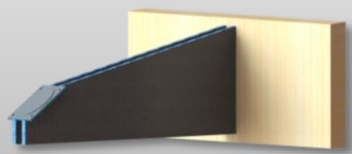
Integrated System

=

Wing Section

+

Housing Unit & Support Structure



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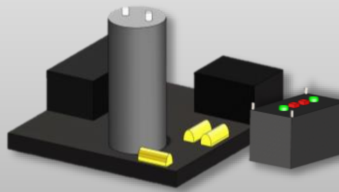
Deicing Mechanism

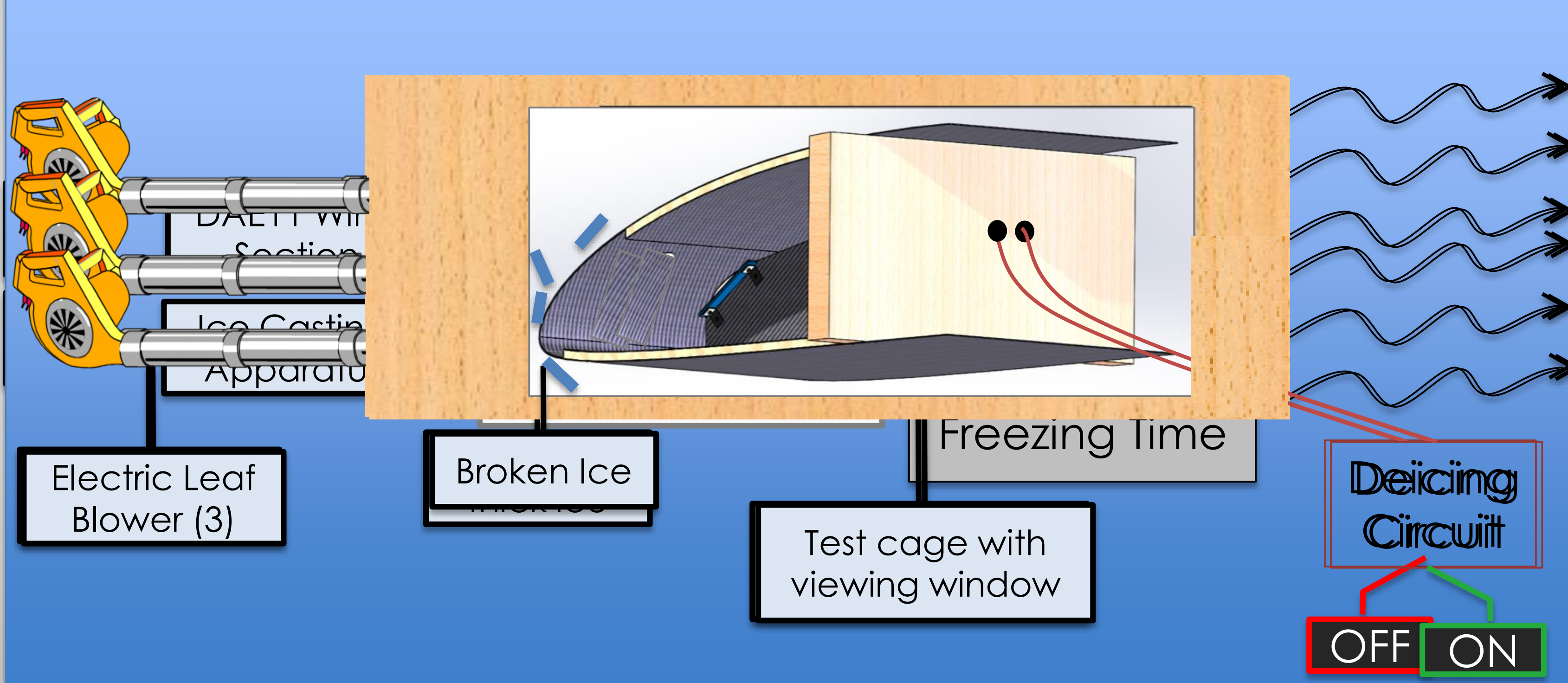


Concept of Operations

Purpose of Level 3:

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

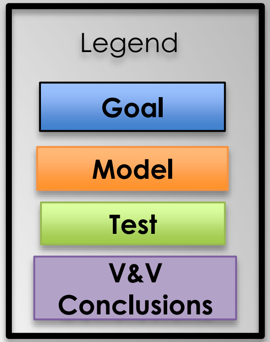
Ice Testing Occurs in Freezer (-15^oF)

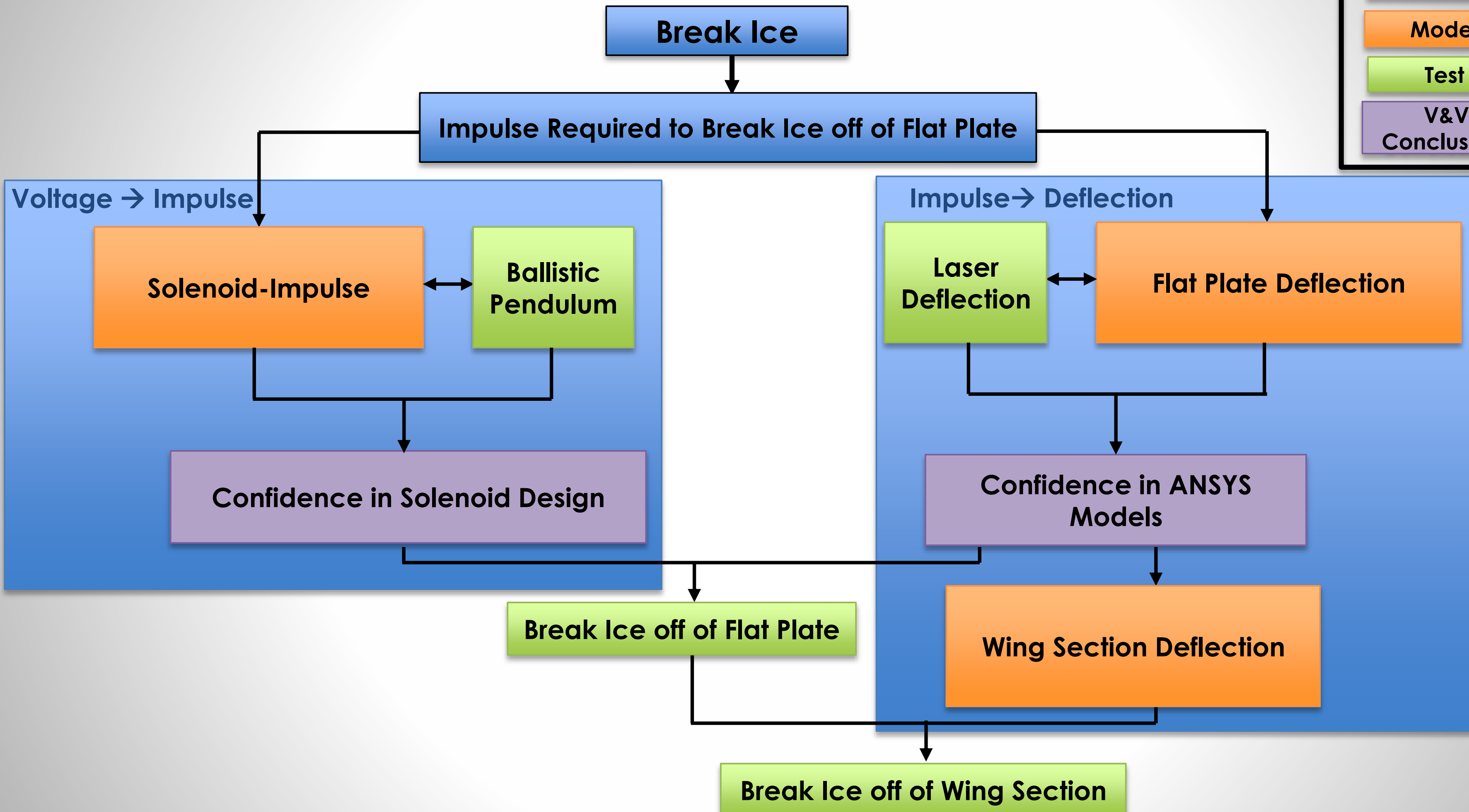


Project Roadmap

Purpose/ Objectives | Design Description | **Test Overview** | Test Results | Systems Engineering | Project Management

Project Roadmap



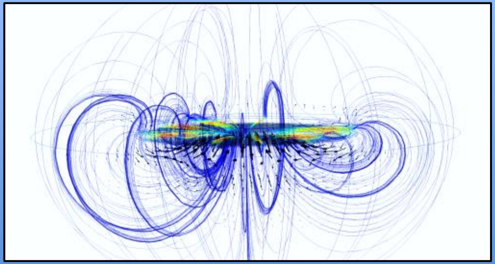


High Level Model Overview

To remove 3/8 inches of ice off of <u>representative</u> wing section…

Solenoid-Impulse Model

- COMSOL- Calculate force based on voltage, solenoid and target disk parameters

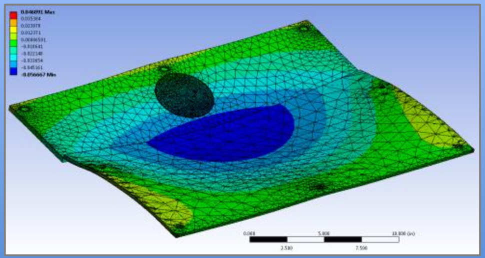


Magnetic Field Lines from Solenoid

Voltage needed to produce force to break ice

Flat Plate Deflection Model

- ANSYS- Calculate expected deflection of carbon fiber flat plate with applied impulse

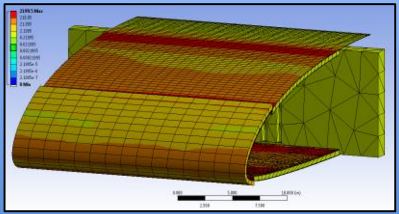


Contour plot of flat plate deflection

Impulse required to break ice off flat plate
0.29 lb-s

Wing-Section Deflection Model

- ANSYS- Calculate force required to break ice
- Model that no structural damage occurs with lifetime usage



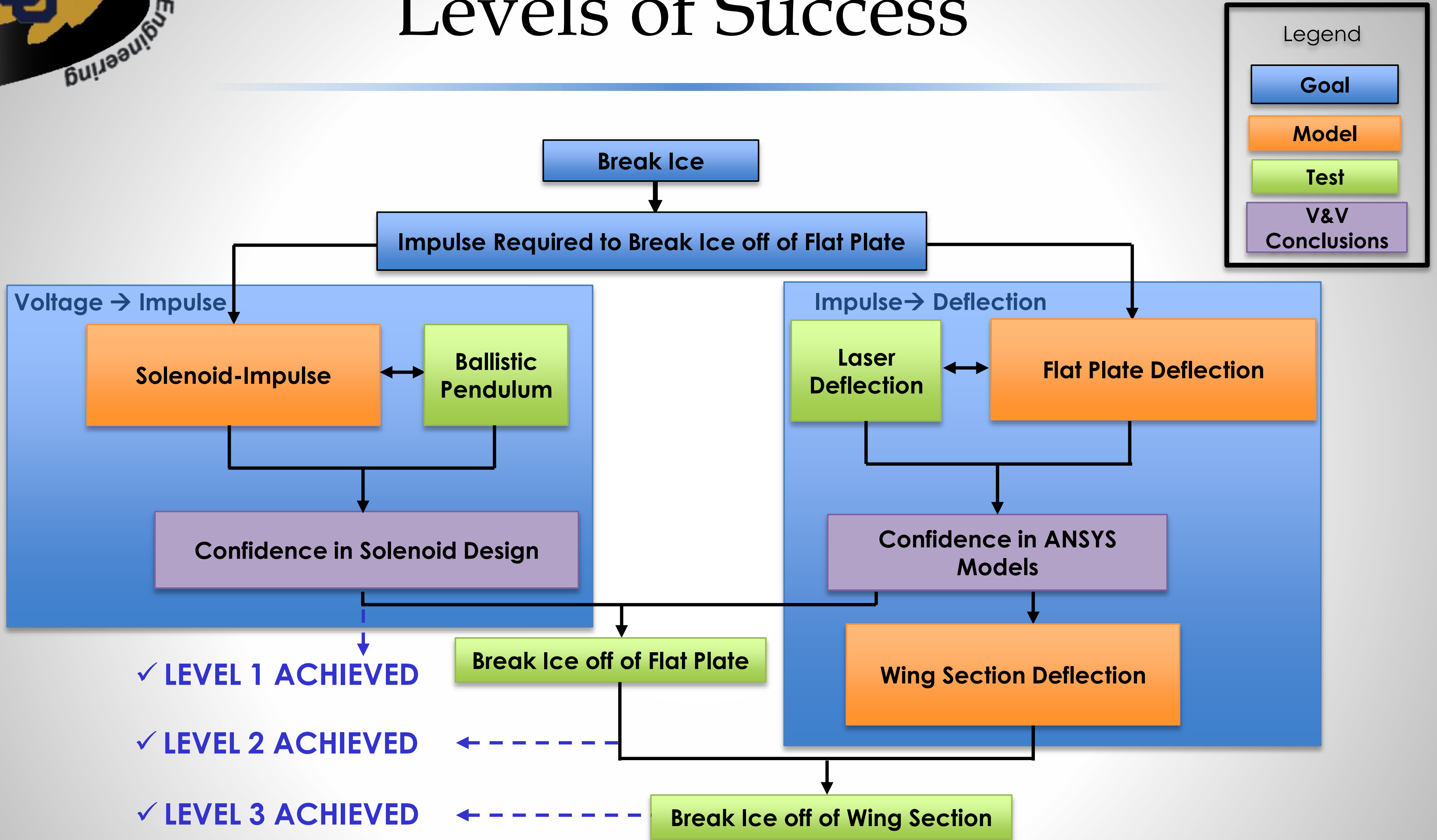
Stress plot for wing section

Impulse required to break ice off wing section
0.26 lb-s

High Level Test Overview

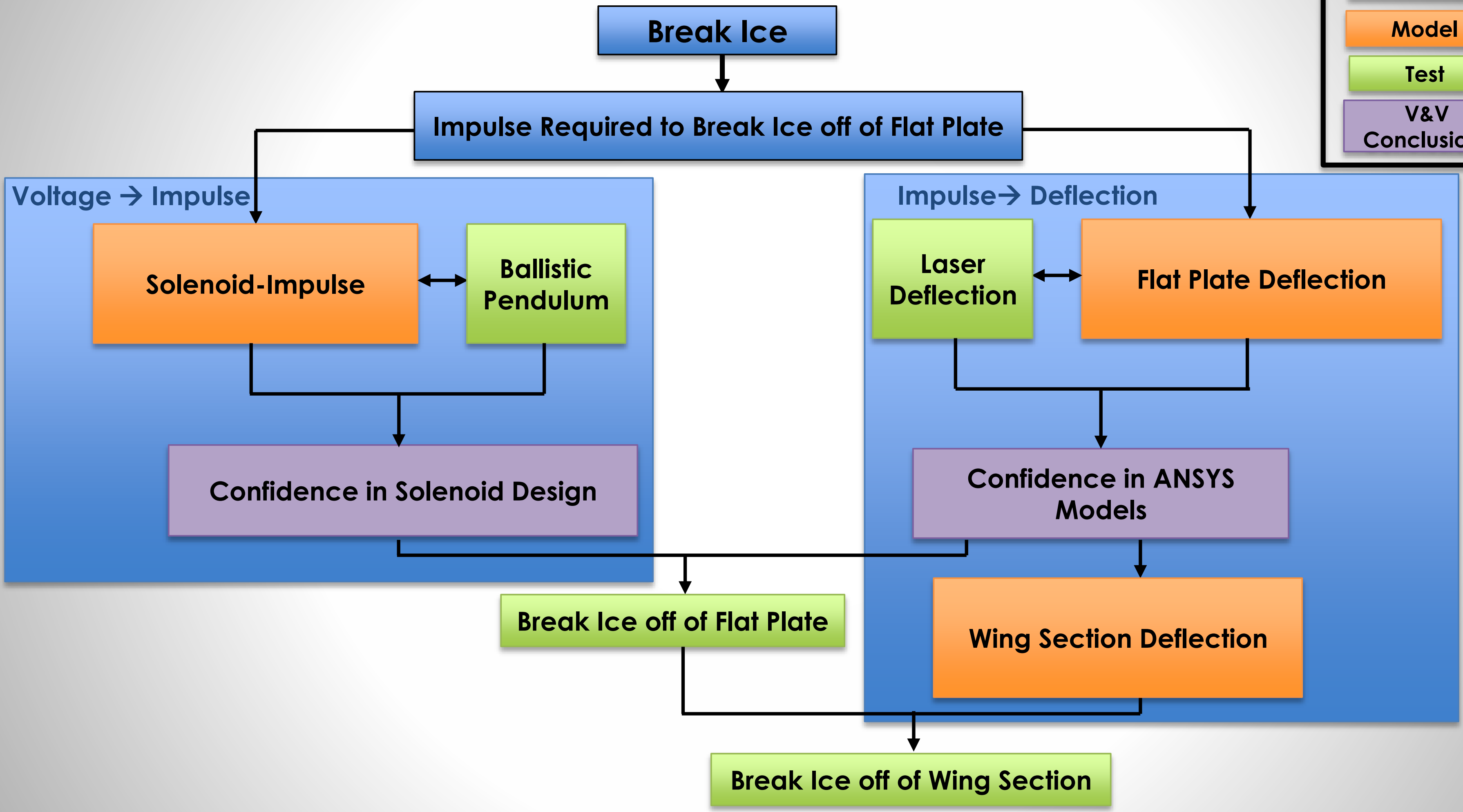
TEST	PURPOSE
Ballistic Pendulum Test	• Verify Solenoid Force Model • Refine design using ballistic pendulum test data
Laser Deflection Test (Flat Plate)	• Measure deflection to verify material properties via Flat Plate Model
Ice Breaking Test (Flat Plate & Wing Section)	• Verify force required to break ice • Prove functionality while meeting power and integration requirements

Levels of Success



Test Results

Level 1: Voltage-Impulse

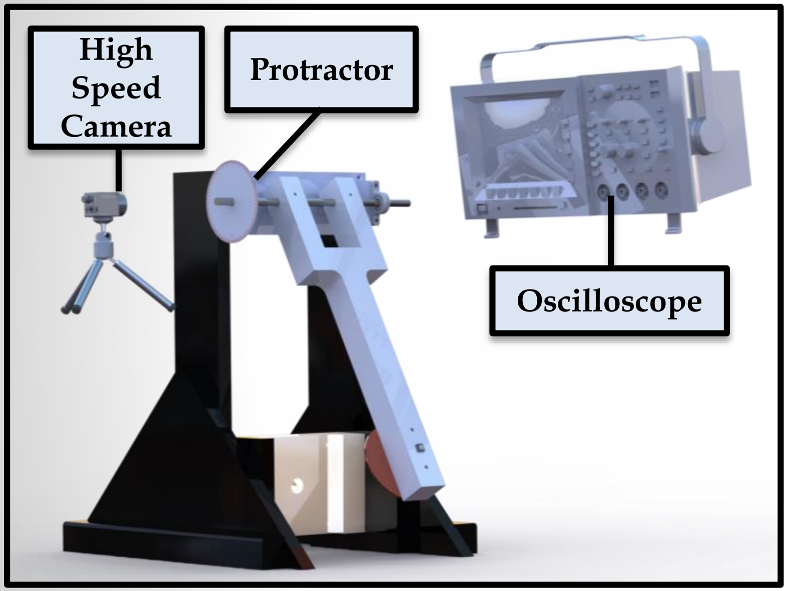


Legend
- Goal
- Model
- Test
- V&V Conclusions

Purpose/ Objectives | Design Description | Test Overview | **Test Results** | Systems Engineering | Project Management

Level 1- Ballistic Pendulum Test Overview

Goal: Verify COMSOL impulse output in order to ensure ballistic pendulum is an adequate tool for measuring impulse



Ballistic pendulum test setup

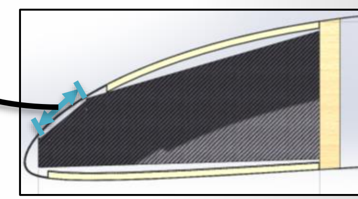
Method to collect impulse vs. voltage data:

Measure **Max Angle** reached by pendulum arm

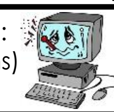
- Use **protractor** & **high speed camera**
- Calculate force/impulse

Testing Specs = COMSOL Specs

Solenoid Outer Diameter Constraint and Gap Distance:
D = 3 in, d = 4 mm



Solenoid # of Turns Constraint: (COMSOL Software Limitations)
N = 36



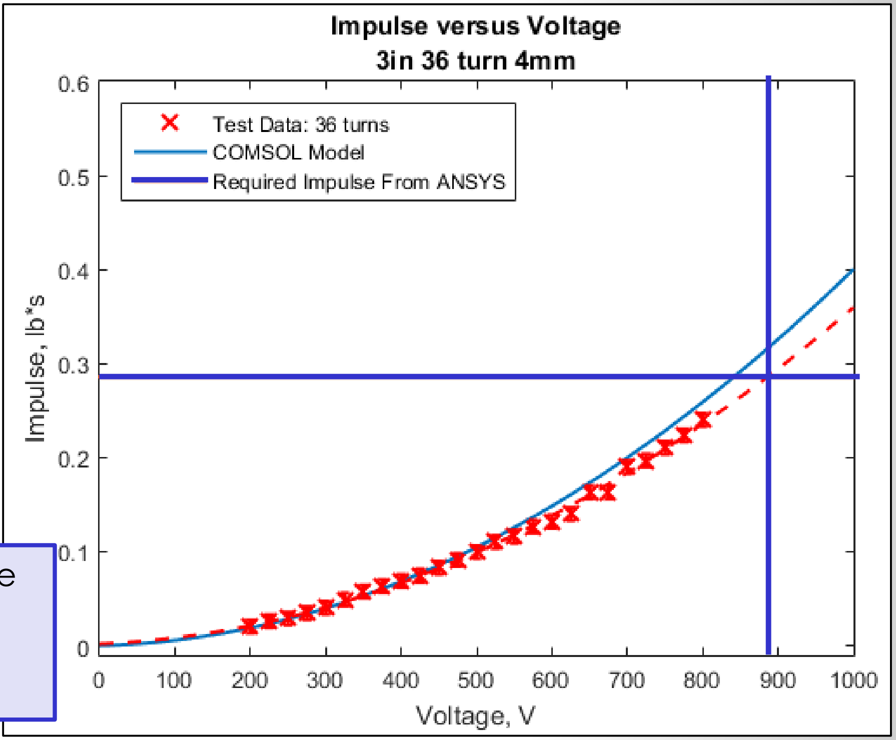
Reqs Verified with Test	DR.3.1	DR.3.2	DR.2.1
	Operate on an **incoming 28 V DC voltage line.**	Instantaneous power draw shall be **at most 2 kW.**	Be capable of **removing 3/8 inch thick ice** on test section

Level 1- Ballistic Pendulum Test Results

COMSOL Model Verification

Testing Specs = COMSOL Specs

- Solenoid outer diameter = 3 in
- Solenoid inner diameter = 0.25 in
- Gap distance = 4 mm
- Number of turns = 36



Conclusions

- Model-predicted impulse matches test results
- Modeling software limitations- based on experimental data trends, solenoid design was improved upon

890V required to produce impulse to break ice off **flat plate** (**0.29 lb-s**) with *model-limited solenoid*

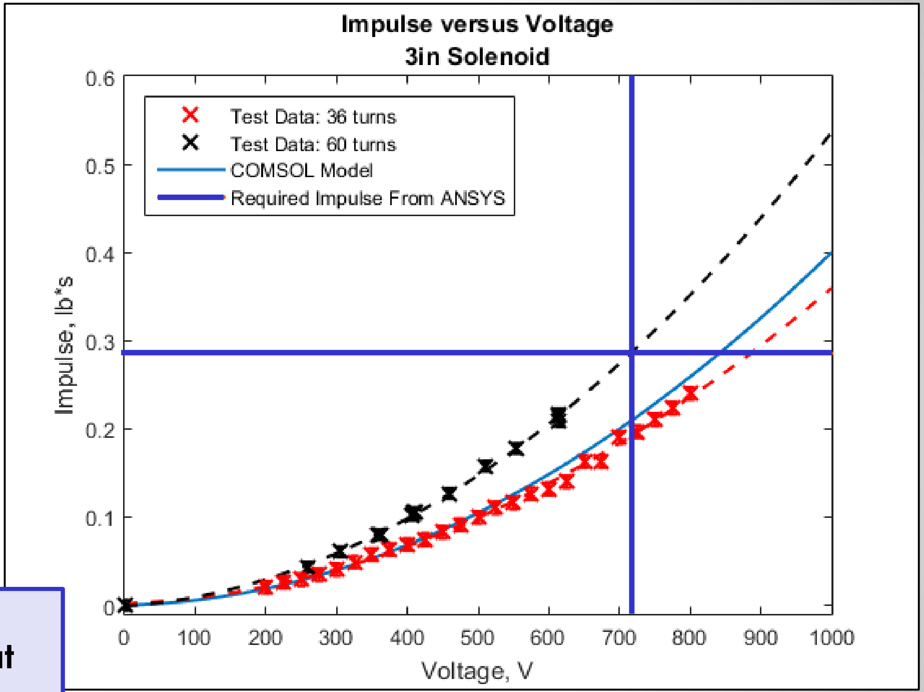
Implications of Model Verification

➔ Verification gives **confidence in test data**
➔ **Test data becomes modeling tool** (model is geometrically limited)

Level 1- Solenoid Design Refinement

Improved Solenoid Design
- Solenoid outer diameter = 3 in
- Solenoid inner diameter = 0.25 in
- Gap distance = 4 mm
- Number of turns = 60 → **Refined Parameter**

Conclusions for Refined Model
- 60-turn solenoid produces greater impulse at less voltage
- Energy-consumption is greater concern over mass consumption
  - 36 Turns → 198 J
  - 60 Turns → 126 J
  - **→ 36% Energy Savings by using 60 turns vs. 36 turns**

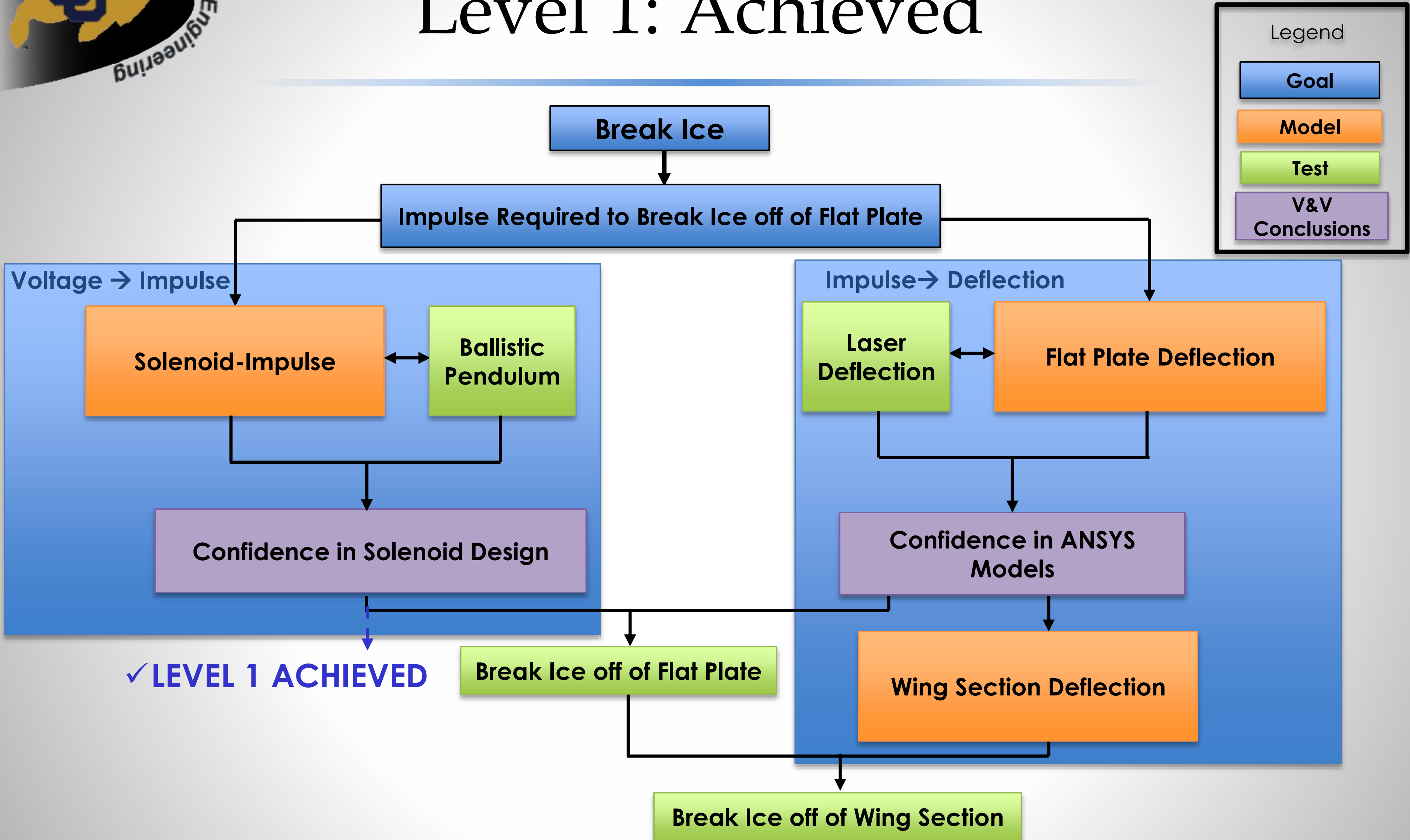


710V required to produce impulse to break ice off **flat plate** (**0.29 lb-s**) with *max number of turns solenoid*

Level 1 Success Conclusions:

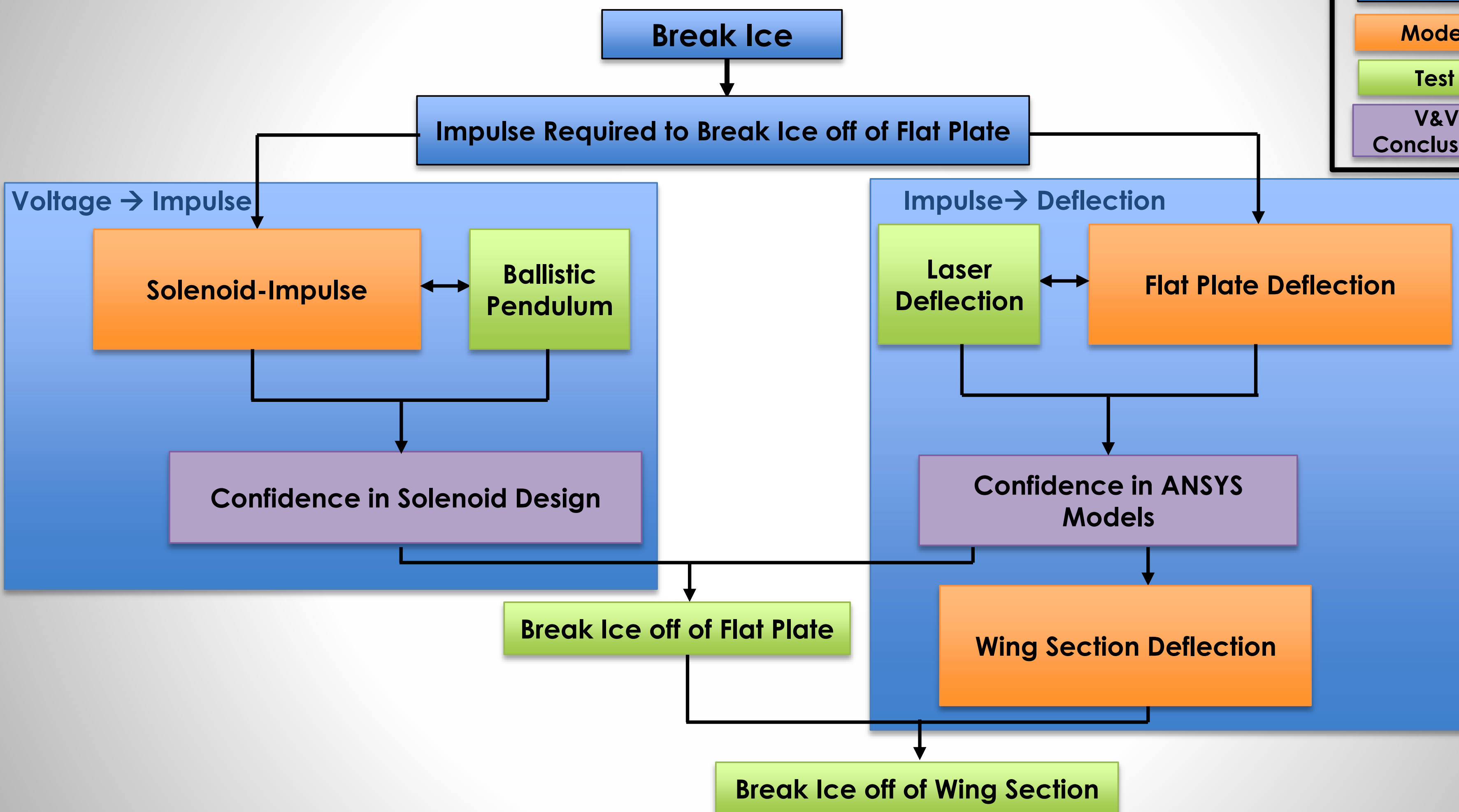
✓ DR.2.1	✓ Mechanism produces impulse required to break ice
✓ DR.3.2	✓ Energy consumption = 126 J

Level 1: Achieved



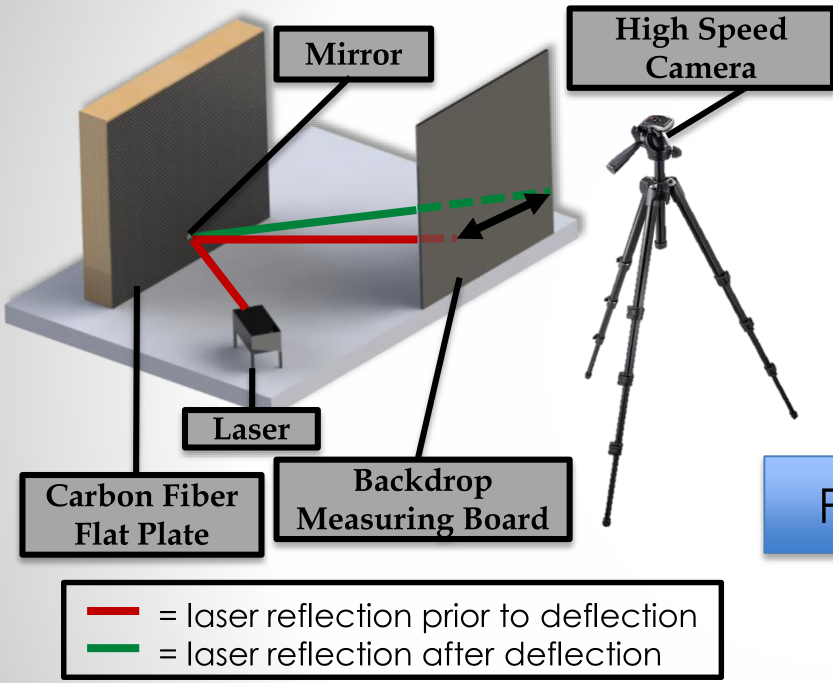
Level 2: Impulse-Deflection

Legend
- Goal
- Model
- Test
- V&V Conclusions



Level 2- Flat Plate Deflection Test Overview

Goal: Verify ANSYS force model through deflection measurements



Method to measure surface deflection

- Altered geometry from actuation
  - Reflected laser displacement
- High speed camera
  - Long exposure against ruler

Predicted flat plate deflection* = 0.3 in

**Corresponds to measureable deflection without ice at force required to break ice*

Reqs Verified with Test	DR.1.3	DR.2.1
	Operation shall **not damage or degrade** wing	Be capable of **removing 3/8 inch thick ice** on test section

Level 2- Flat Plate Deflection Test Results

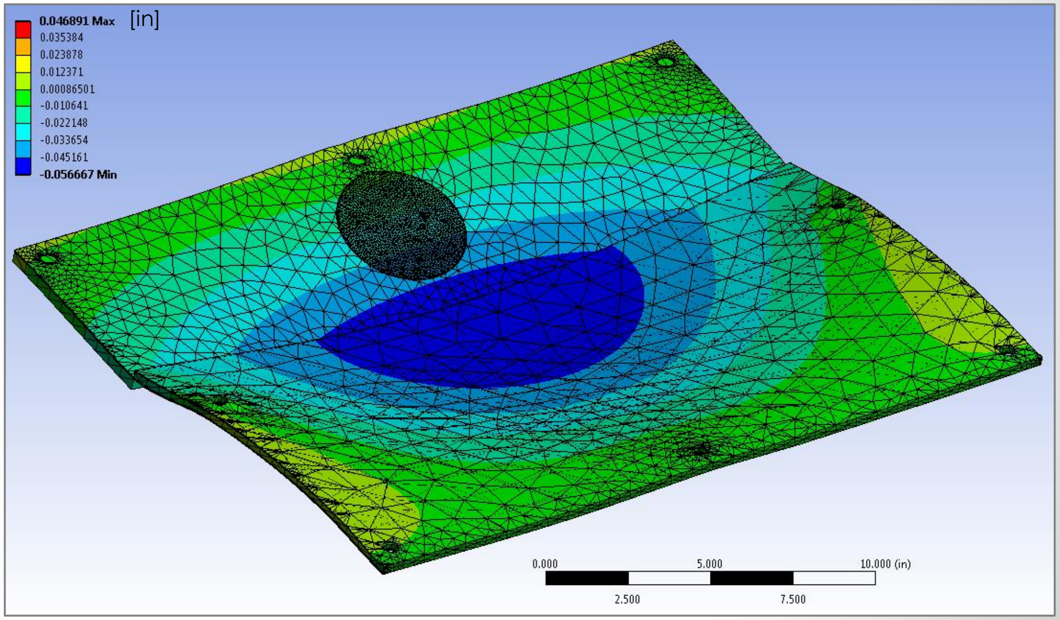
Test conditions match Flat Plate Model conditions

- Boundary conditions = 8 fixed points (corners & mid-sides)
- Impact location same in ANSYS and test

Recall

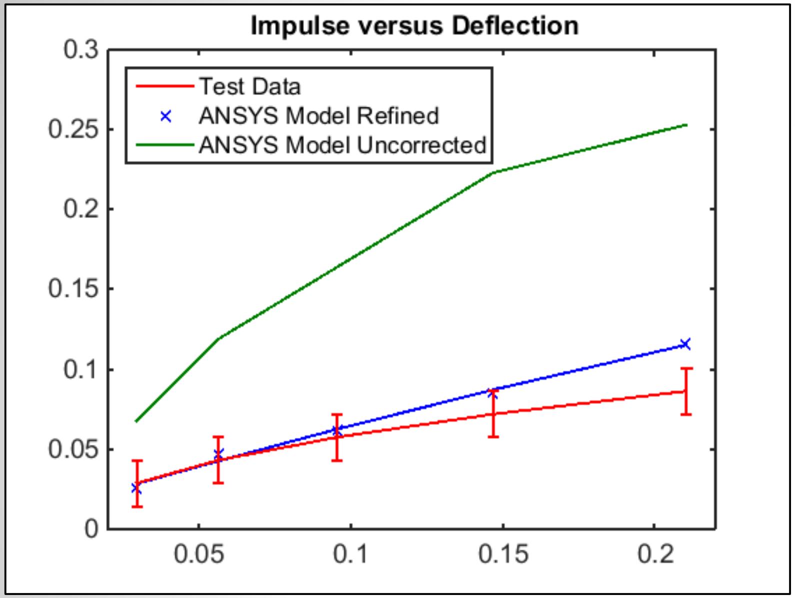
0.29 lb-s = Impulse required to break 3/8 inches of ice off flat plate

Modeled as pressure applied over target disk area



ANSYS Flat plate deflection model with Impulse = 0.29 lb-s

Level 2- Flat Plate Model Refinement



Refinement

- Carbon Fiber Young's Modulus
  - Starting value = 61340 MPa
  - Refined value = 213400 MPa
- Original value based on research, new value from actual material

Predicted (extrapolated) **deflection** measurement (no ice) at impulse required to break ice off flat plate = **0.092 in ± 0.014 in**

✓ DR.1.3

✓ DR.2.1

Level 2 Deflection Test Conclusions:

- ✓ Refined material properties for further confidence in models (ice breaking predictions)
- ✓ Carbon fiber deflects enough from mechanism impulse to theoretically break ice

Level 2- Flat Plate Ice Removal Test Results

Purpose: check functionality of ice breaking on simple geometry

Testing conditions
- 3/8 in ice thickness
- -15°F ambient temperature
- Actuated at 615V

- First Blast: Removed ~50% of the ice.
  - After blast #1: Cracks had fully propagated through the ice.
- Second Blast: Removed an additional ~45%.

Initial

Impulse #1

Impulse #2

Level 2 Deflection Test Conclusions:

✓ Refined material properties for further confidence in models (ice breaking predictions)

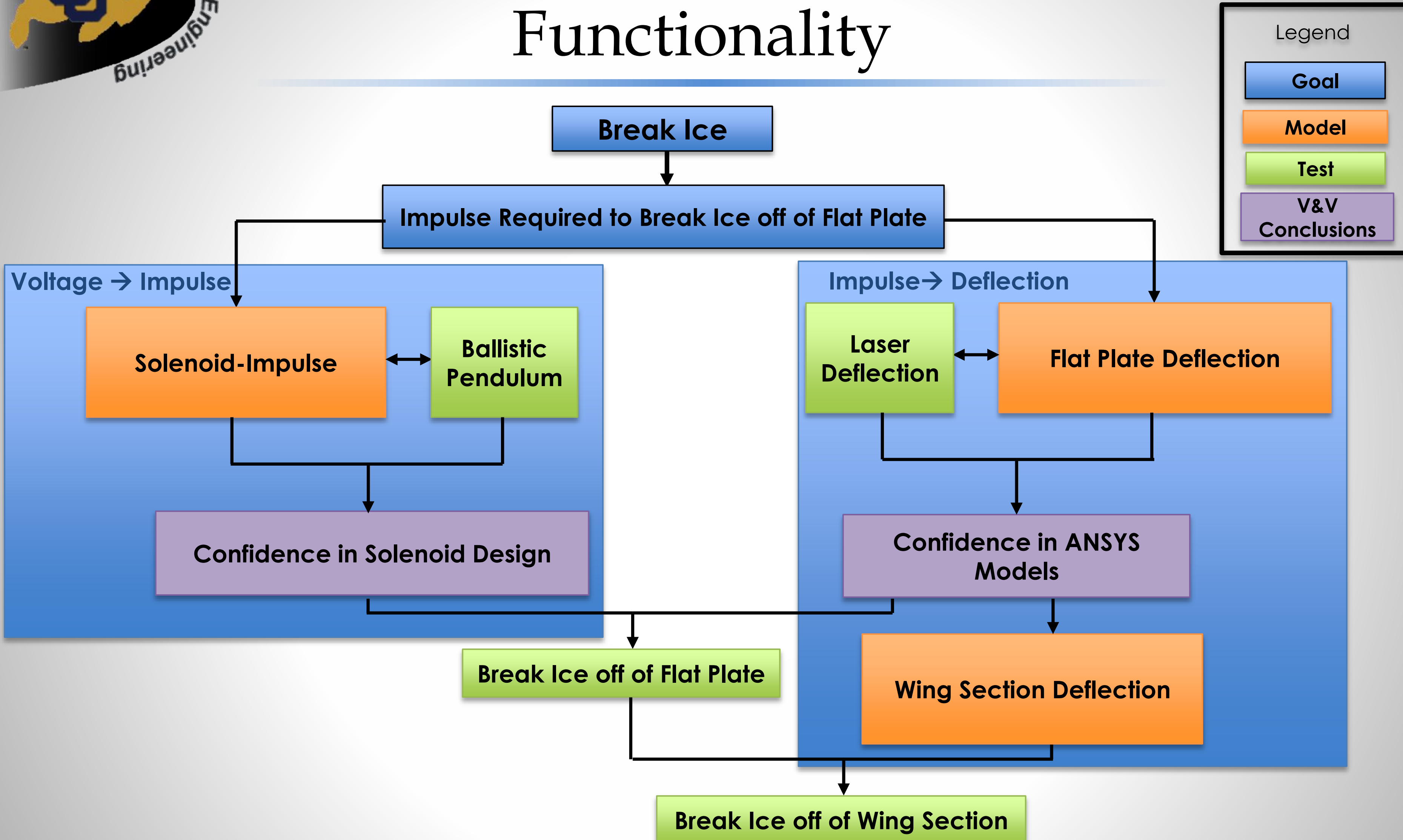
✓ Carbon fiber deflects enough from mechanism impulse to theoretically break ice

✓ DR.1.3

✓ DR.2.1

Level 2: Achieved

Level 3: Integration & Functionality



Level 3- Wing Section Test Overview

Goal: Proof of functionality while meeting design requirements.

Wind cage, wind speed, test section setup in walk-in freezer

Testing Environment

- Location: walk-in freezer at INSTAAR
- Testing temperature range = -15°F → 0°F
- Wind speed = 65 knots average (at leading edge)

Testing Procedure

- Setup wing section to cast ice (~ 4 hrs)
- Prepare wing section in wind cage (& leaf blowers) for testing
- Transport mechanism, power supply into freezer
- Turn on leaf blowers, actuate mechanism with flat plate/full wing section
- If ice remaining, charge & actuate until *clear*

Reqs Verified with Test	DR.1.2 Deicing mechanism shall be **integrable with DAE1I-shaped wing**	DR.2.1 The deicing mechanism shall **remove 3/8-inch thick ice**	DR.2.3 **Max thickness** of ice **remaining = 0.1 inches**

Level 3- Wing Section ANSYS Model

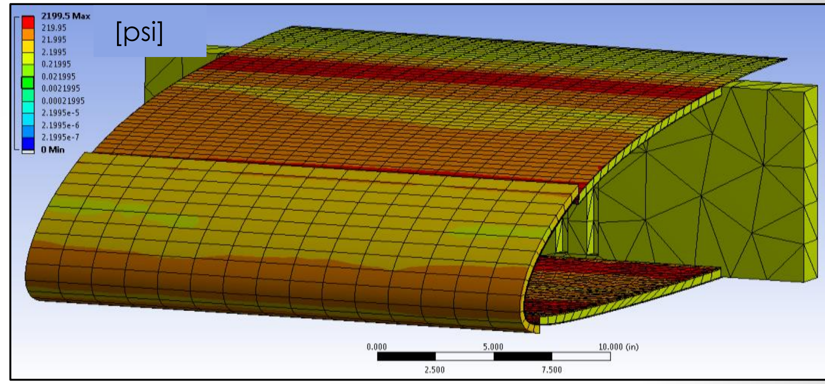
Model Properties

Boundary Conditions

- Fixed at the spar

Modulus Values

- E for carbon fiber = **61.34 GPa**
- E for nomex honeycomb = **255 MPa**



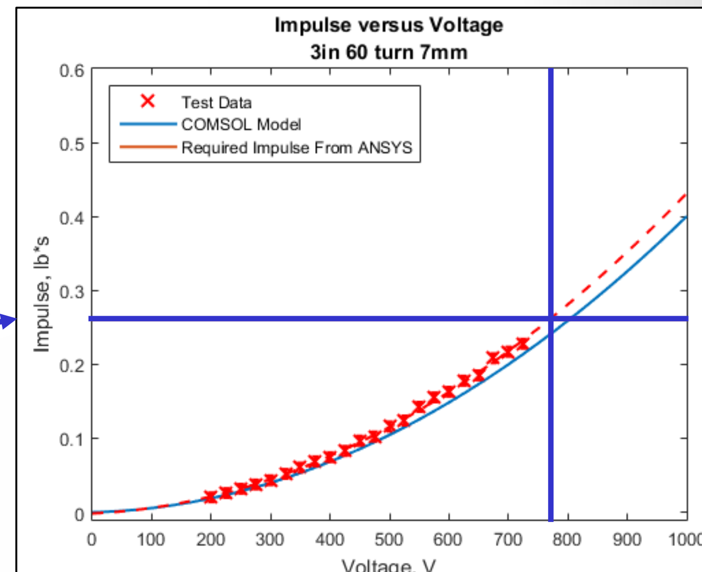
Integrated Mechanism Properties

Modulus Values

- Solenoid Diameter = 3 inches
- Target Disk Diameter = 3 inches
- Gap Distance = 7 mm

Required Impulse from ANSYS to break ice off WING SECTION = **0.26 lb-s**

Actuate mechanism at (minimum) 770V to break ice.



Level 3- Wing Section
Ice Removal Test Results

ANSYS predicted a Impulse of 0.29 lb-s → This is equivalent to 710 V

Testing done at 612 V

Initial

Impulse #1

Impulse #2

Impulse #3

Level 3- Wing Section Ice Removal Test Results

900 Volts = 0.35 lb-s

- First Blast: Removed ~80% of the ice.
- Second Blast: Removed all remaining big chunks.

900 Volts only required 2 blasts

After blast #1: Cracks had fully propagated through the ice.

Blast #1

Blast #2

Level 3 - Wing Section Ice Removal Test Results

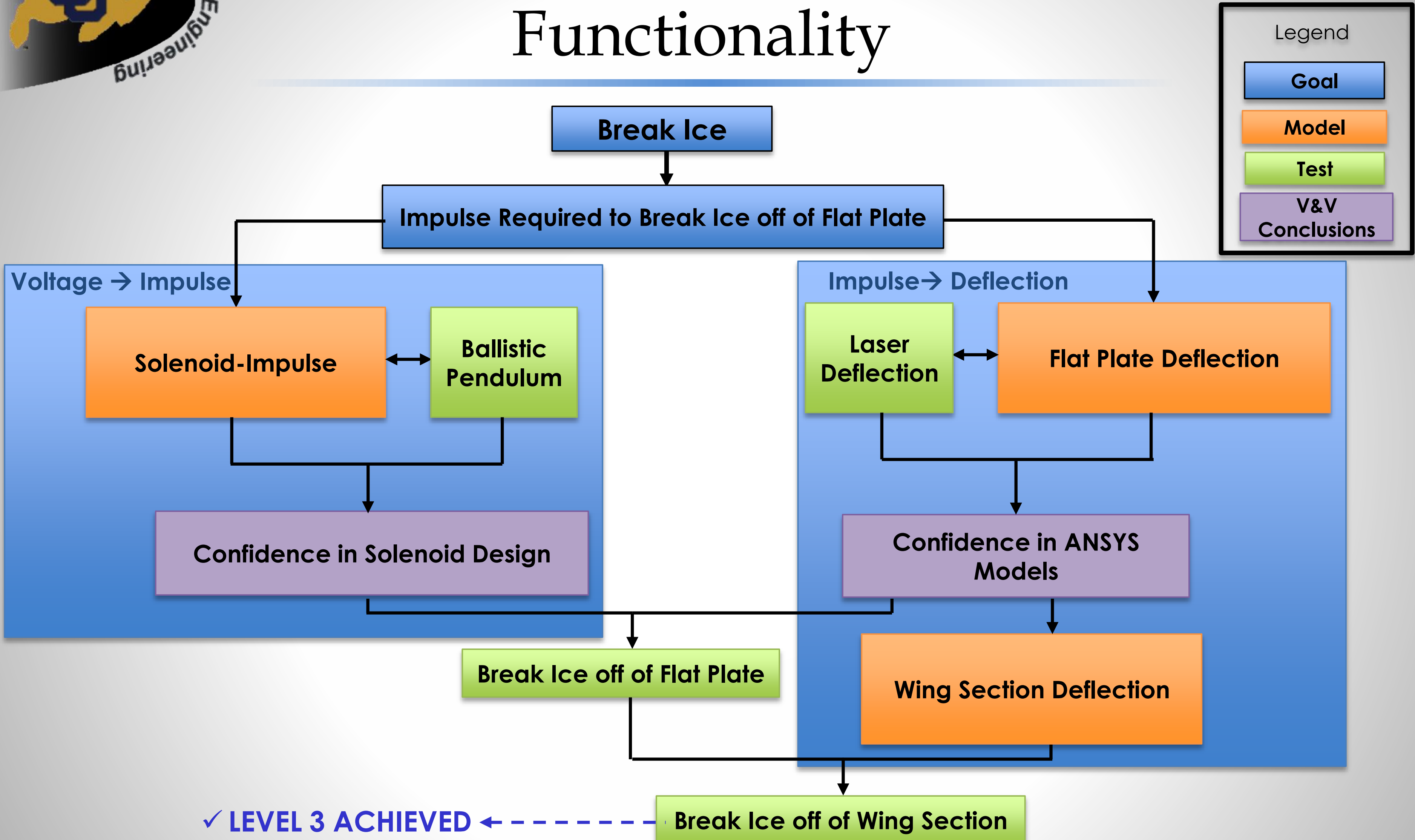
Summary of Results:

- **Mechanism successfully broke ice → Proof of functionality**
- **Higher voltages → Fewer impulses needed**
- **Ice removal hindered by adhesion → Should be modeled in the future**
- **Remaining ice had a depth of > 0.1 in → May disrupt laminar flow**

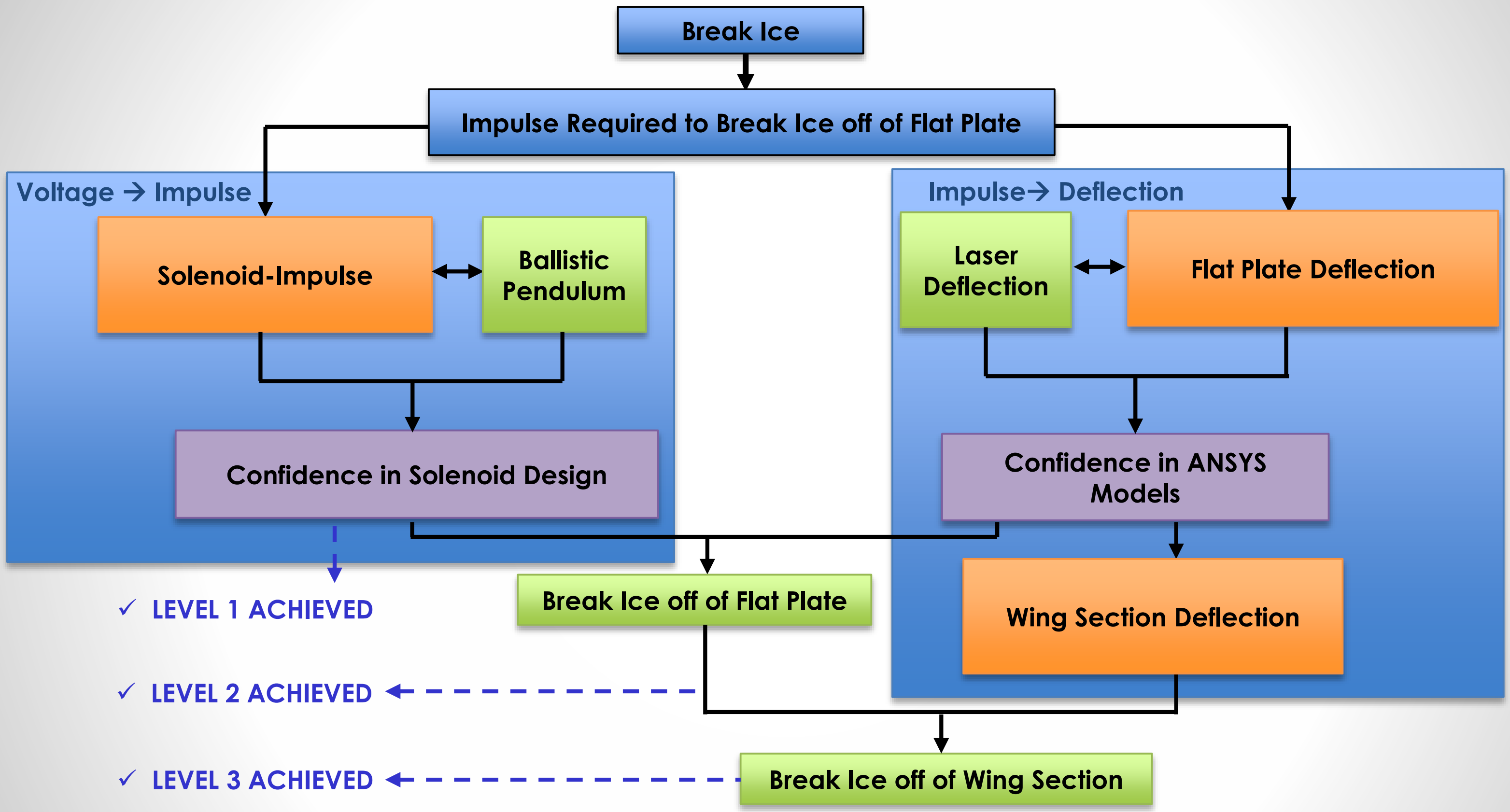
Level 3 Ice Removal Requirement Summary:

✓ DR.1.2	✓ System successfully integrated within DAE11 test section
X DR.2.3	X Maximum ice thickness after actuation was greater than 0.1 in.
✓ DR.2.1	✓ The deicing mechanism shall be capable of removing 3/8 in thick ice on test section.

Level 3: Integration & Functionality



Conclusions from Levels



✓ **ALL 3 LEVEL ACHIEVED**
Lessons Learned:

- Recap solenoid selection
- Flat Plate Model refinement based on material properties
- Requires refinement of Wing Section Model based on refined material properties and on ice adhesion

Full Scale Integration

Orion UAV takeoff[3]

From testing, 1 Solenoid clears 2 ft. section of ice off wing section
→ For full-span, deicing requires **62 solenoids + Housing + Supporting Circuitry**

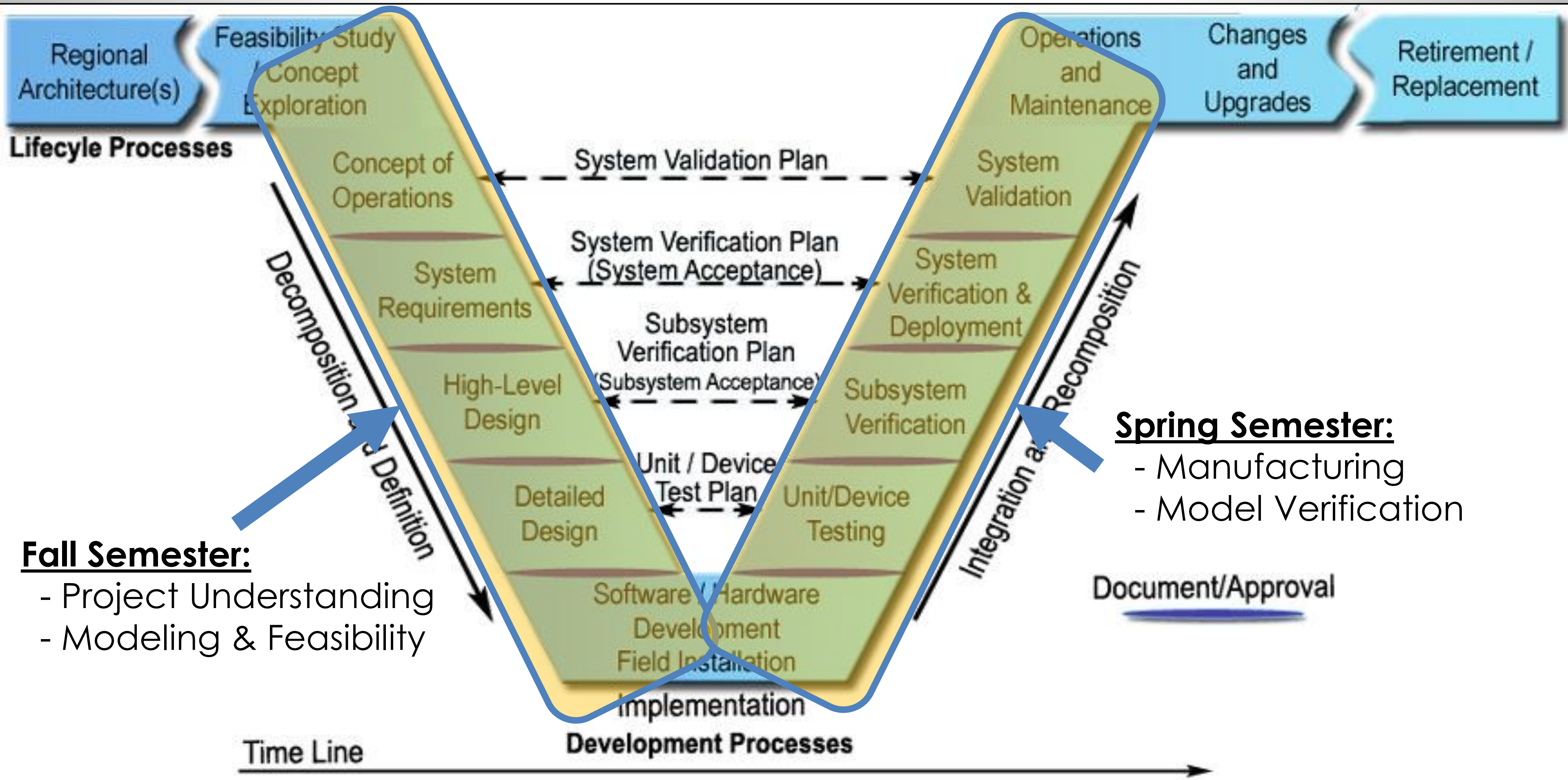
Total Mass Estimate = 200 lb.

Total Power Estimate = 310 W to recharge and fire at 5 minute intervals

Note: requires further testing to account for extra rigidity of ORION wing ribs and further testing on ice crack and shed areas

Systems Engineering

Systems Engineering



Fall Semester:
- Project Understanding
- Modeling & Feasibility

Spring Semester:
- Manufacturing
- Model Verification

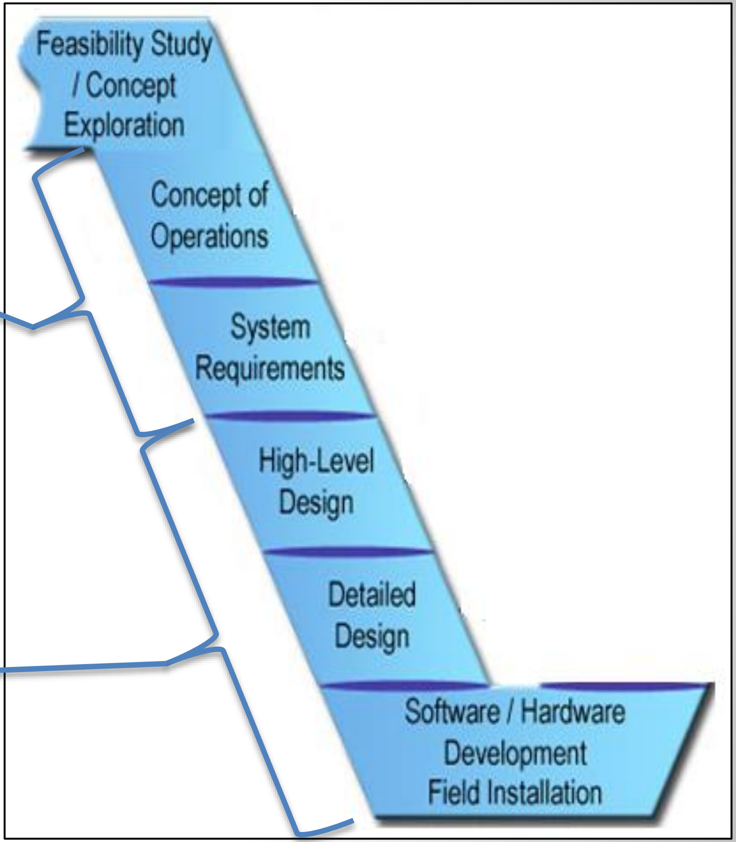
Fall Semester

Major Tasks
- Gain scope of project
- Determine Levels of Success
- Develop requirements to accomplish scope

Major Difficulties
- Customer was vague about project desires
- Hard to put numbers to parts of project

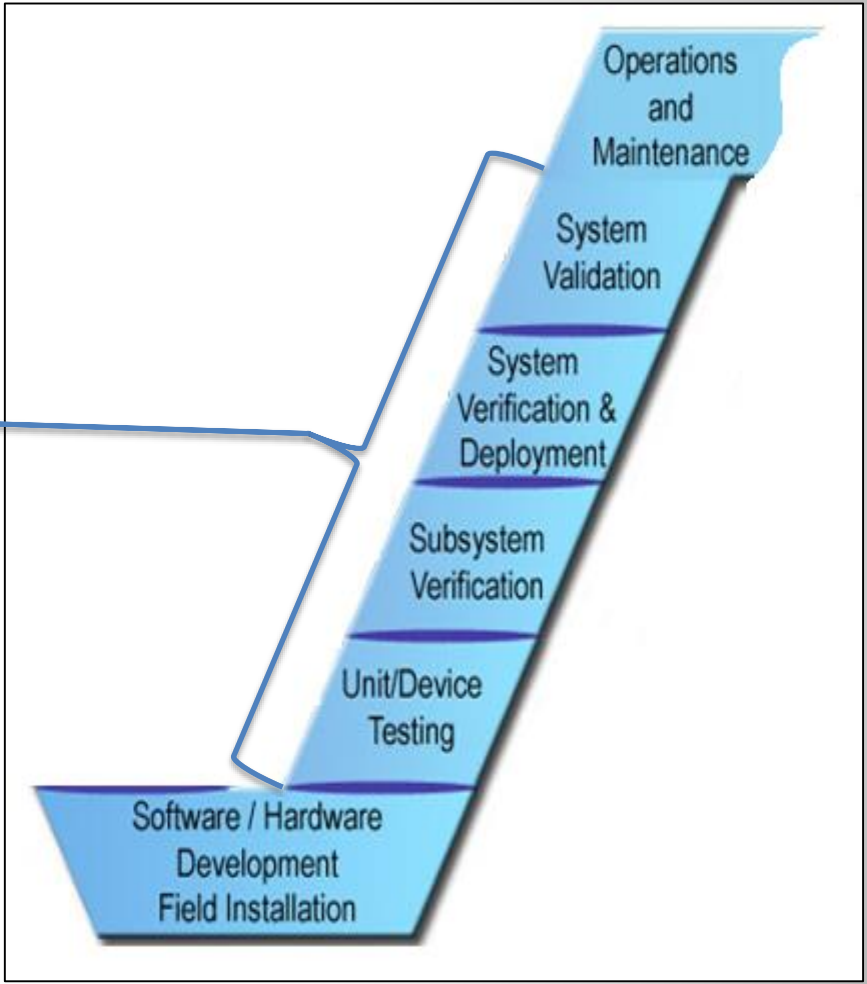
Major Tasks
- Model required force to break ice
- Model solenoid force

Major Difficulties
- Figuring out model for solenoid
- Distributing tasks among team
- Solving design choice and not changing



Spring Semester

Major Tasks
- Manufacture tests for levels of success
- Perform tests
- Build models for interpreting test data
Major Difficulties
- Building ballistic pendulum
- Scheduling for shipping
- Capturing Laser Deflection



Lessons Learned

Fall Semester:

- Don’t lean on customer for whole project scope.
- **REALLY** know project before moving forward.
- Engineers model then validate.

Spring Semester:

- Don’t expect to get it right the first time it’s re-built.
- Shipping takes 2X longer than expected.
- Shipping costs 2X more than expected.

Project Management

Project Management

PDD, CDD

CDR, FFR

Successes

~ **Early planning** for testing accommodations
~ **Execution** for all 3 levels of success
~ **Team dynamic** & communication

Challenges

~ **Defining** project
~ Keeping **progress** high when project is at a low
~ Maintaining **communication**
~ **Consistent distribution** of tasks

LESSONS LEARNED

- **Margin** is critical – in both **TIME** and **BUDGET**
- **Communication** & **passion** are the driving forces behind team **success**
- **It is physically possible to break ice using electromagnetism**

SFR, PFR

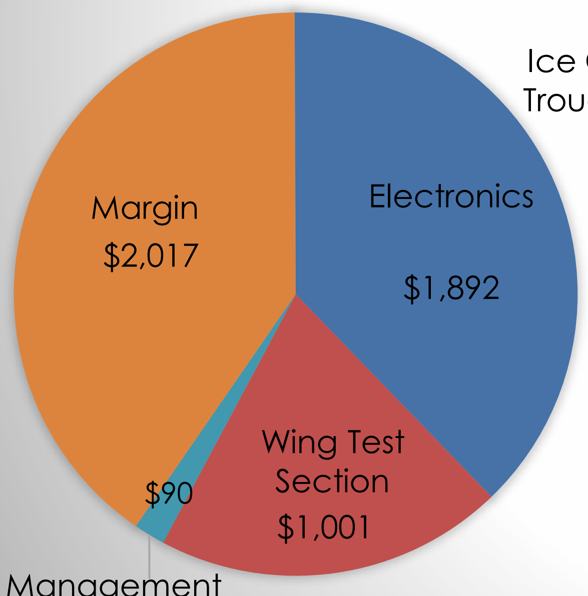
TRR

MSR

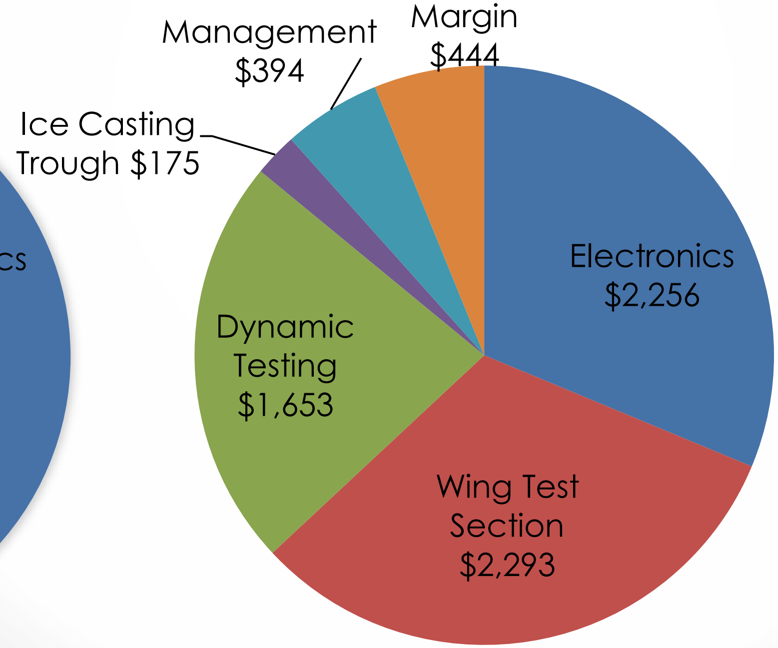
Budget Comparison

Budget: Aerospace Department: **$5,000** + EEF: **$2,215** → Total Available Budget: **$7,215**

CDR Budget



Actual Budget



Total Expenses: $6,771 (94%)

Remaining Budget: $444

Unforeseen Expenses:

- Useless $700 fan
- Sophisticated mechanism assembly
- Layup Materials
- Ballistic Pendulum
- Leaf Blowers
- Printing & poster costs

Future Purchases:

- Printing Project Final Report

Industry Cost

Total Team Hours = **3,685**

Contribution	Cost
Team Hours	$115,156
Including 200% overhead cost	$115,156
Material Cost	$6,771

Total Industry Cost: **$237,083**

***Assumes $65k salary for each team member*

Project Conclusion

An electromagnetic deicing system is a ***VIABLE*** solution for deicing the Orion UAV

Questions?

References

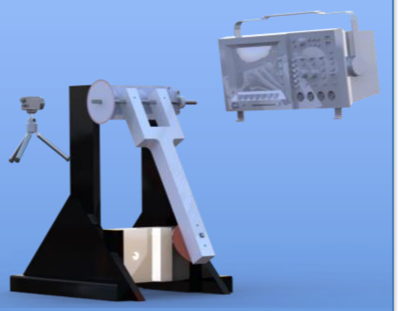
[1]"Ice on the wing of the NASA Twin Otter," UCAR, 2005 URL: http://www.ucar.edu/communications/staffnotes/0412/ice.html [citied 11 Oct. 2015].

[2]"Flight Global:- Aurora's Orion UAV in Storage after USAF World-record Flight - SUAS News." *SUAS News*. N.p., 16 Sept. 2015. Web. 19 Apr. 2016. <http://www.suasnews.com/2015/09/flight-global-auroras-orion-uav-in-storage-after-usaf-world-record-flight/>.

[3] Warwick, Graham. "Aurora Claims Endurance Record For Orion UAS."*Aviation Week*. N.p., n.d. Web. 19 Apr. 2016. <http://aviationweek.com/defense/aurora-claims-endurance-record-orion-uas>.

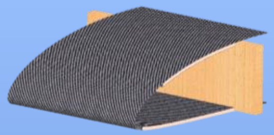
Critical Project Elements

Ballistic Pendulum

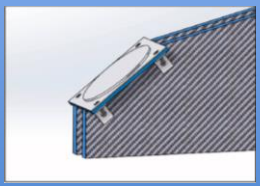


Pendulum Assembly

Wing Section

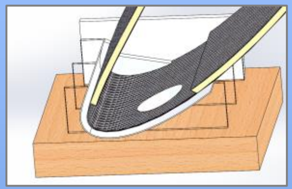


Test Section

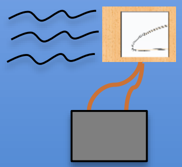


Housing Unit & Support Structure

Test Setup

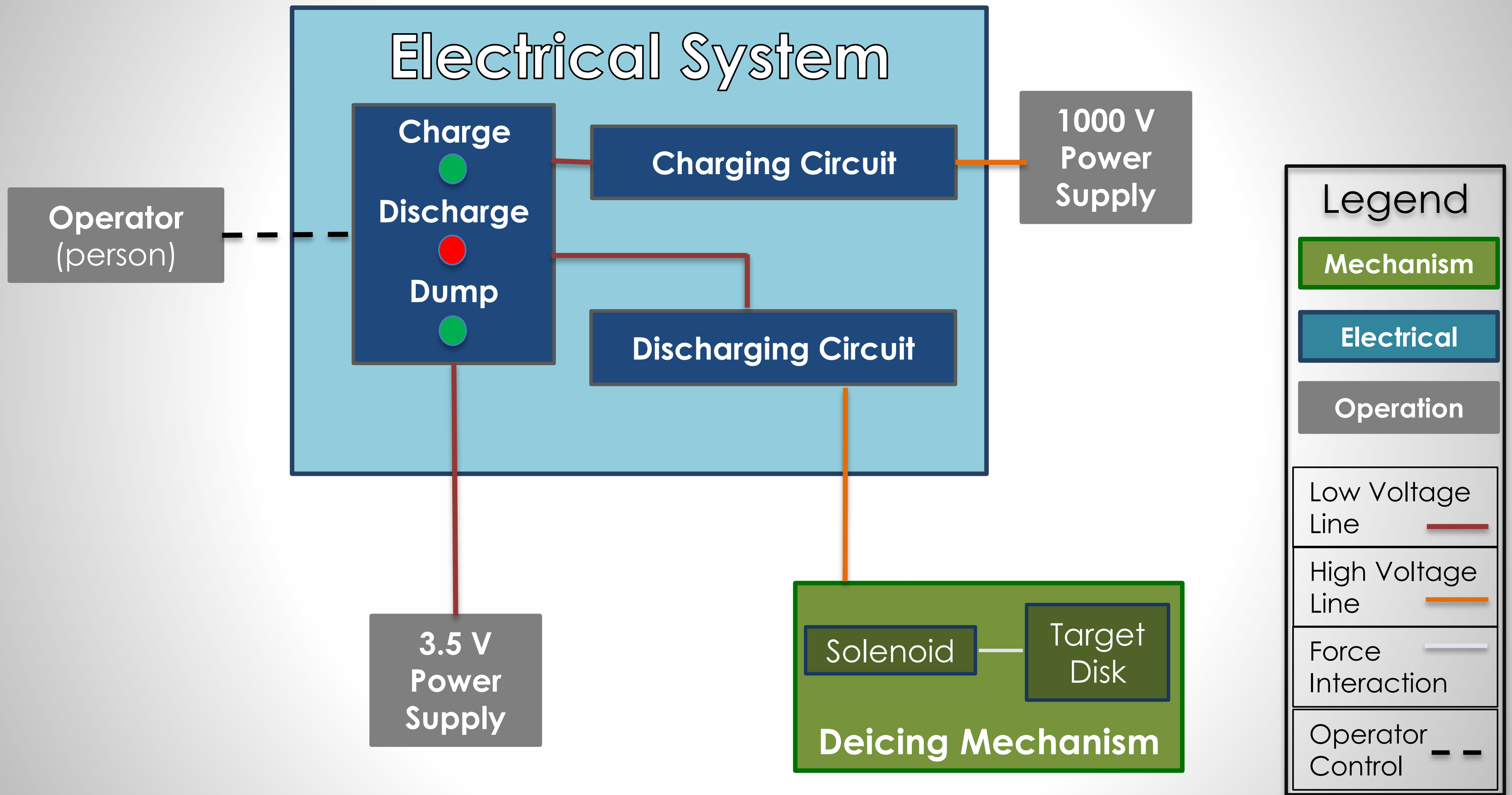


Ice Casting



Wind Speed & Test Cage

Functional Block Diagram



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.

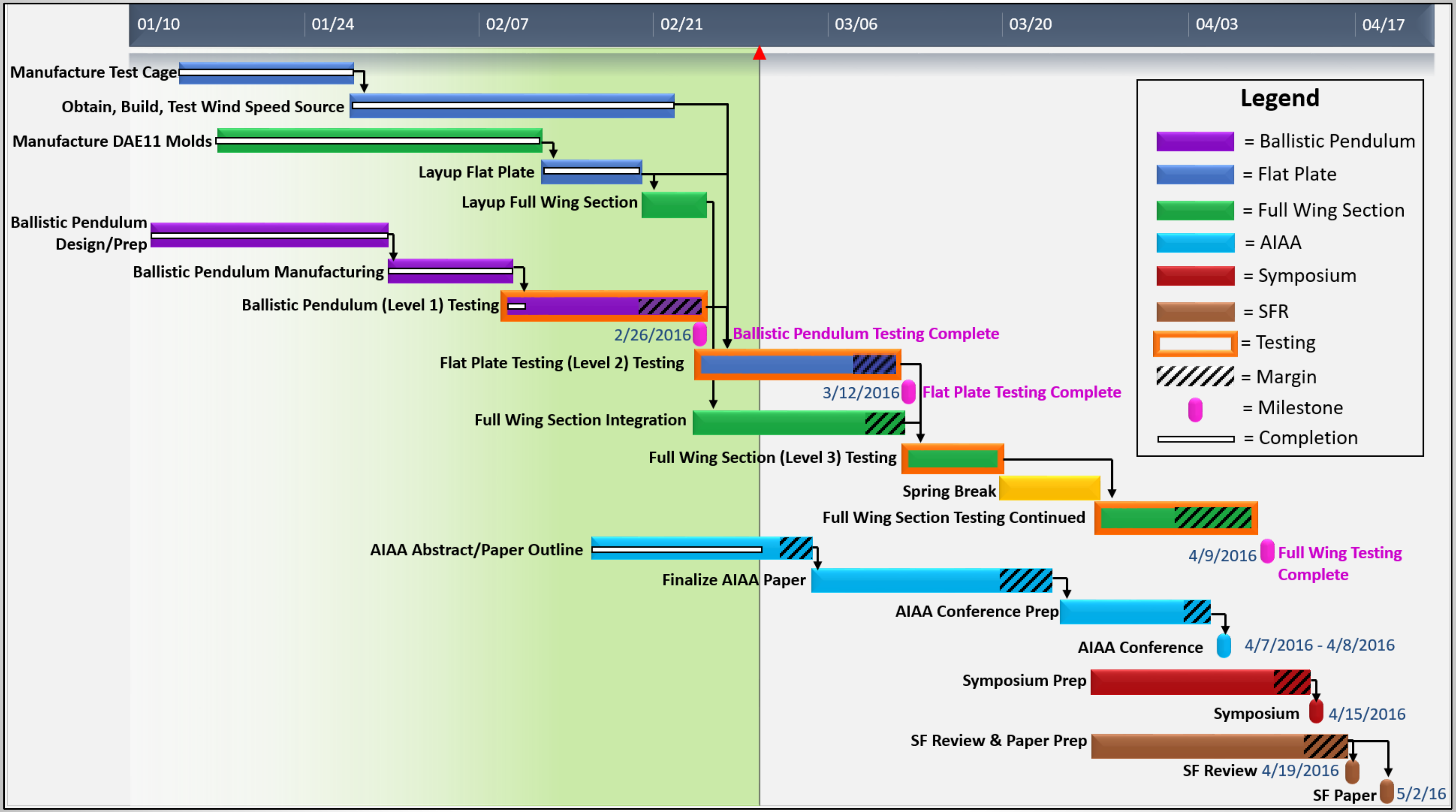
Requirements – FR2

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.

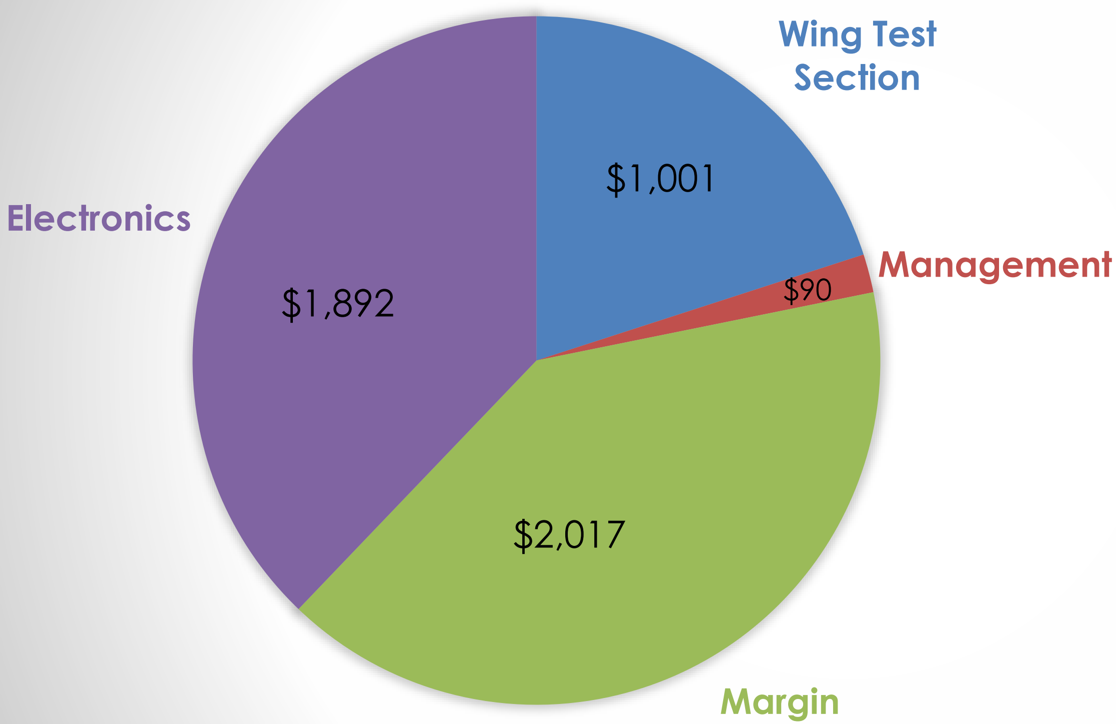
Requirements – FR3

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.

Backup - TRR Schedule



Backup - CDR Cost Plan



Manufacturing
- Test Section
- Housing Unit
- Ice Cast Mold

Electronics
- Circuit
- Solenoid

Management
- Gantt Chart

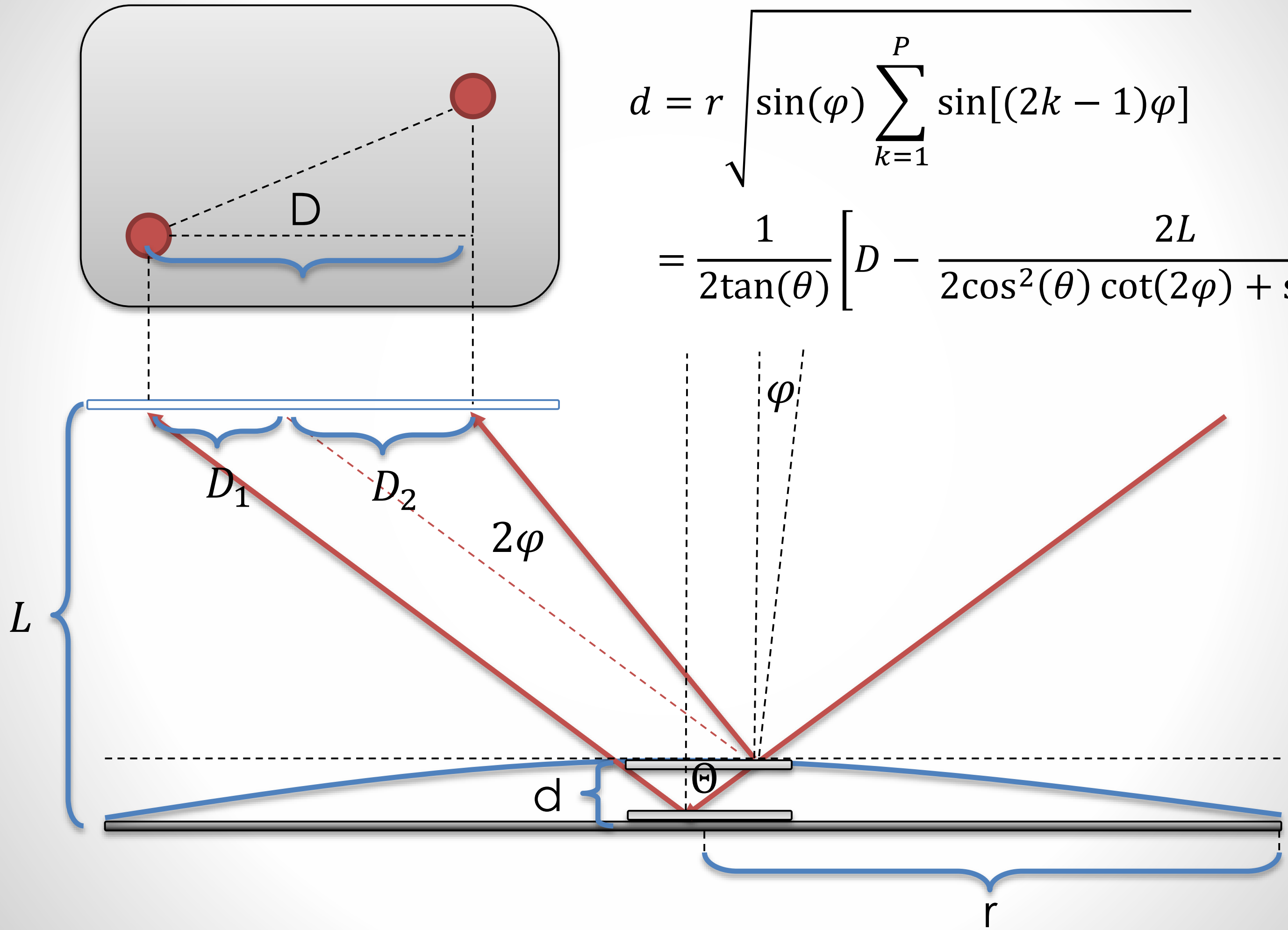
Total Expenses: $2,983

Margin: $2,017

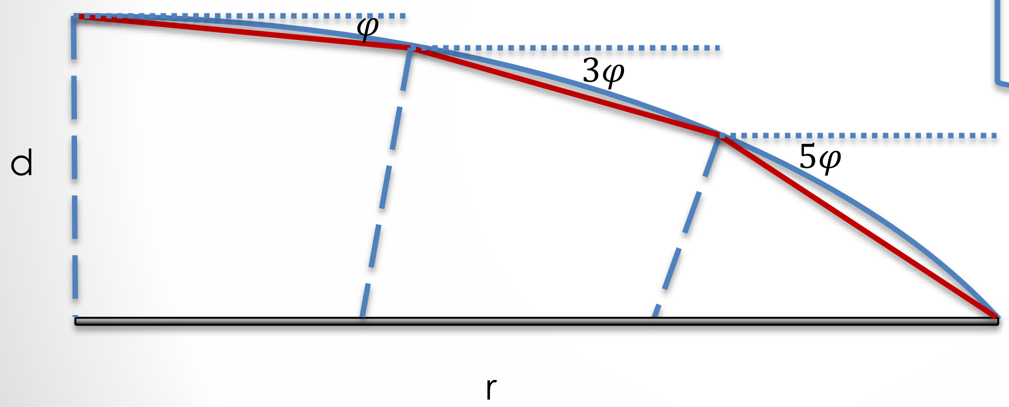
Deflection Measurement

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

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



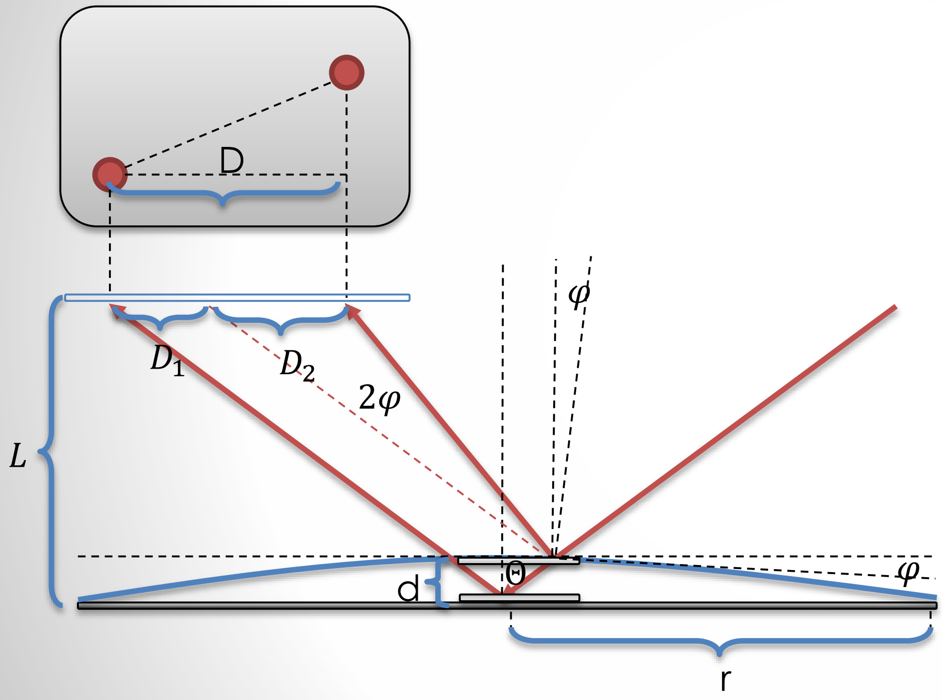
Backup Slides for Equation



$$\begin{cases} d = 2R\sin(\varphi)\sum_{k=1}^{P}\sin[(2k-1)\varphi] \\ r = 2R\sin(\varphi)\sum_{k=1}^{P}\cos[(2k-1)\varphi] \end{cases}$$

$$R = \frac{r^2}{2d}$$

Backup Slides for Equation



$$D = D_1 + D_2 = 2d\tan(\theta) + \frac{L\sin(2\varphi)}{\cos(\theta)\sin\left(\frac{\pi}{2} + \theta - 2\varphi\right)}$$

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

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

Switch from Avg. Force to Impulse

- We cannot apply the exact waveform applied by our solenoid in ANSYS. And because the time is short, impulse will better account for the differences.

- Average force is deceptive. It is completely possible to have a higher overall average force, but be less effective.

- Reduces error due to time assumptions. Our current average force models make assumptions for discharge time. Using impulse removes these assumptions.

Level 1- Ballistic Pendulum Impulse Calculations

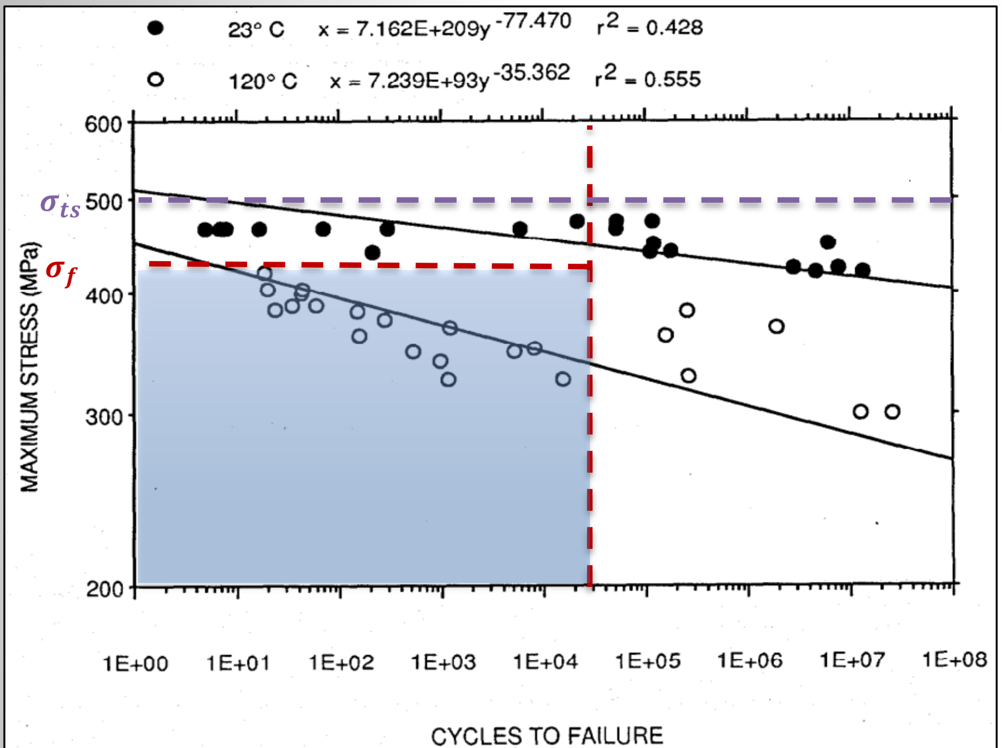
$$PE = mgh = mg[L_{com}(1 - cos\theta)]$$

$$\omega = \sqrt{\frac{2PE}{I}}$$

$$V_{com} = \omega * L_{com}$$

$$Impulse = V_{com} * \mathrm{m}$$

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**