University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

AESIR
Actuated Electro-magnetic System for Ice Removal

Conceptual Design Document

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1.0 Information

1.1 Project Customer

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2.0 Project Description

2.1 Purpose

In-flight icing represents a serious problem for all aircraft. It increases drag, causes premature stalls, and may even immobilize the aircraft's control surfaces. It is for these reasons that many aircraft are outfitted with ice protection systems (IPS), which prevent large buildups of ice on the aircraft surface. Unfortunately, many IPSs negatively impact aerodynamic performance or require large amounts of power to be effective. This is especially problematic for extreme endurance aircraft such as Aurora Flight Science's Orion Unmanned Air Vehicle (UAV), where low power consumption and high lift to drag ratios are key to its success.

This project will design and construct a small-scale prototype IPS for the leading edge of the Orion UAV wing that will consume less than 4 kW-hr and decrease the lift-to-drag ratio of the airfoil by no more than 10%. The system will be integrated with a representative airfoil section and, once activated, will remove accreted ice from the leading edge of the test section. In order to conduct such a test, an ice application system will be developed that is capable of applying ice with a uniform thickness of 0.36 in. to the test section. The deicing system will also be capable of being scaled-up by Aurora Flight Sciences (AFS) to be integrated with the Orion UAV.

2.2 Objectives

The overall objective of the project is to design, build, and test a prototype de-icing system as a proof of concept for a full de-icing system. The full-scale system is meant for the Orion UAV, therefore the prototype will be designed and analyzed to fit integration requirements with the vehicle. Project success is defined in incremental steps.

Level one success consists of the successful manufacturing of the de-icing mechanism, modeling of the mechanism power consumption and aerodynamics (if the system is implemented externally), and performance testing to verify power consumption requirements. Another important aspect of level one success is developing the ability to form ice on a test section to the desired thickness; this includes forming the ice on an 18 in. long carbon fiber rod (with diameter 2.25 in.) to a thickness of 0.36 in. over a 180° section. Completion of level one allows the project to progress to higher success defined in level two.

The second level consists of the mechanism (from level 1) integration into/onto a test section that approximates an airfoil via geometric composite shapes (i.e. half cylinder for leading edge attached to flat plates for upper and lower surfaces). In addition, level two includes performance testing on the mechanism de-icing capabilities in a cold, windless environment (i.e. wind speed = 0 ft/s).

Level three success brings the project to the highest accomplishment; the de-icing mechanism will be integrated into/onto a DAE11 airfoil shaped test section and the de-icing capabilities verified. Performance testing will now be conducted in a cold, dynamic environment (wind speed > 0 ft./s) via placing the test section with the de-icing mechanism on a workstation and using a compressor to create a wind speed directed at the leading edge. Additionally, the power consumption software model will be validated; this includes comparing test data to the power model to ensure that this aspect of the project is well quantified will do this. Essentially, the objective levels are designed to incrementally progress the prototype through full development and testing. This will verify the designs' capabilities and prove that the mechanism can be scaled up by AFS for implementation on the Orion UAV.

2.3 Concept of Operations

While this project shall eventually be scaled by AFS for implementation on the Orion UAV, the product must also achieve the aforementioned levels of success within the scope of this project's requirements. Thus, two ConOps are depicted below; Fig. (A) demonstrates the procedure for testing the system with the available resources at the University of Colorado at Boulder, and Fig. (B) shows the eventual full-scale use of the system with Orion.

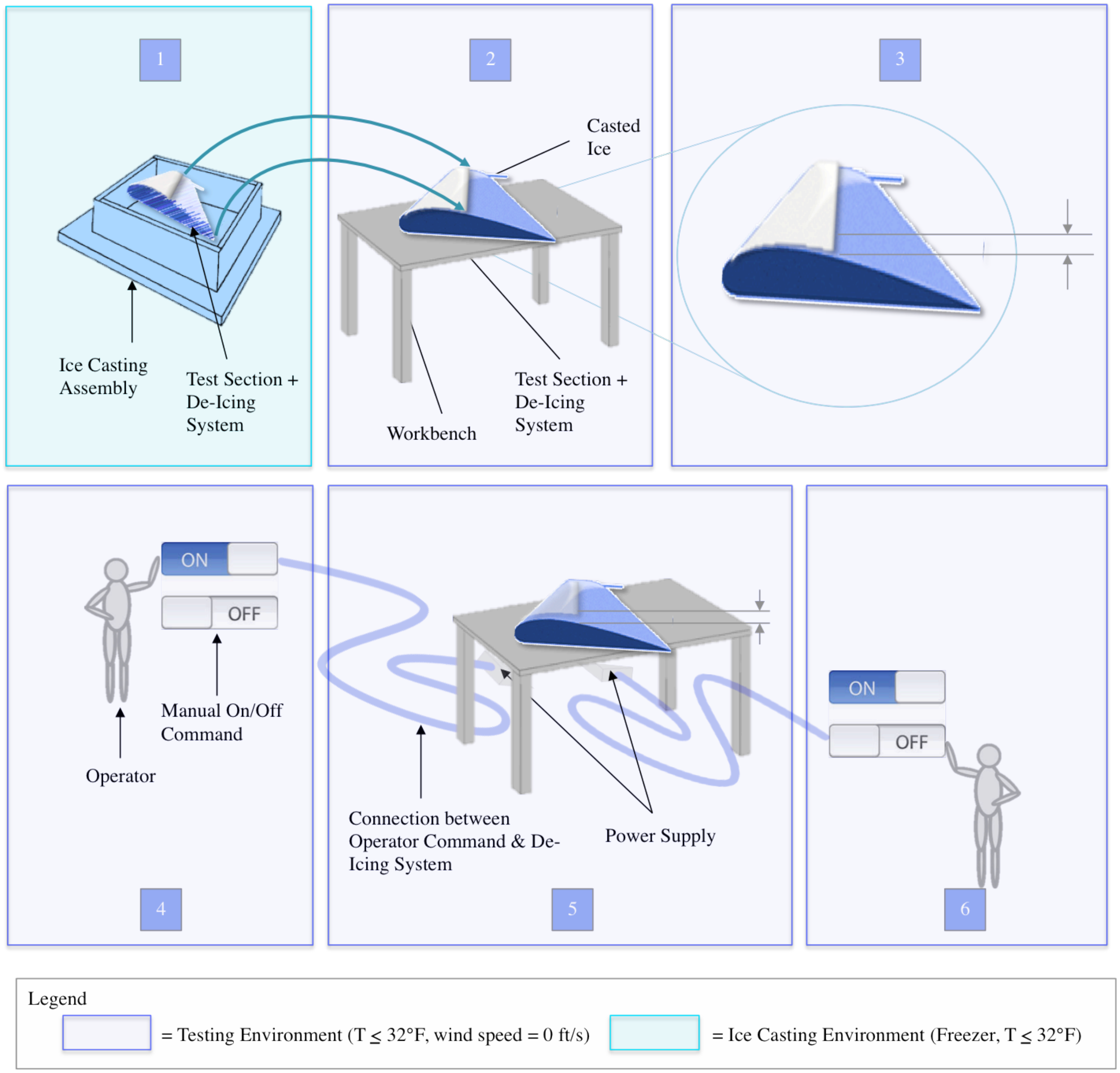


Figure 1. Project scope conops

As identified in Fig. (1), the project concept of operations includes 6 primary steps depicting the sequence of events to occur during the testing phase in the spring semester. This procedure is further described below:

1. **Ice Casting** – Prior to testing, the ice must first be cast onto the test section in a freezer environment.
2. **Transfer** – Once the ice is cast, the assembly will be transferred with proper equipment to ensure conduction does not occur causing the ice to melt during transition to the testing environment.
3. **Volume Confirmation** – Just prior to activating the de-icing mechanism in the testing environment, the thickness and area of the ice volume will first be measured to ensure accurate data collection.

4. – 6. **Testing** – The operator will activate the de-icing mechanism to remove the ice. Once the ice is measured to be below a certain level, the operator will turn off the system. Upon completing this de-icing cycle, the system will be visually examined to ensure no damage occurred to the de-icing mechanism or the test section.

The concept of operations as shown in Fig. (2) shows how the de-icing prototype developed by the AESIR senior project team will fit in with the Orion overall mission. The figure is a graphical representation of the sections that both Aurora Flight Sciences and the AESIR team will individually complete in order to have a functional full-scale de-icing system. The project team will focus on developing a small-scale prototype for removing ice from a small-scale wing while AFS will be involved more involved in developing the system to communicate with the prototype and effectively use it. AFS will also be in charge of scaling the prototype, developed by the senior project team, to a full-size system that can be integrated with the Orion UAV.

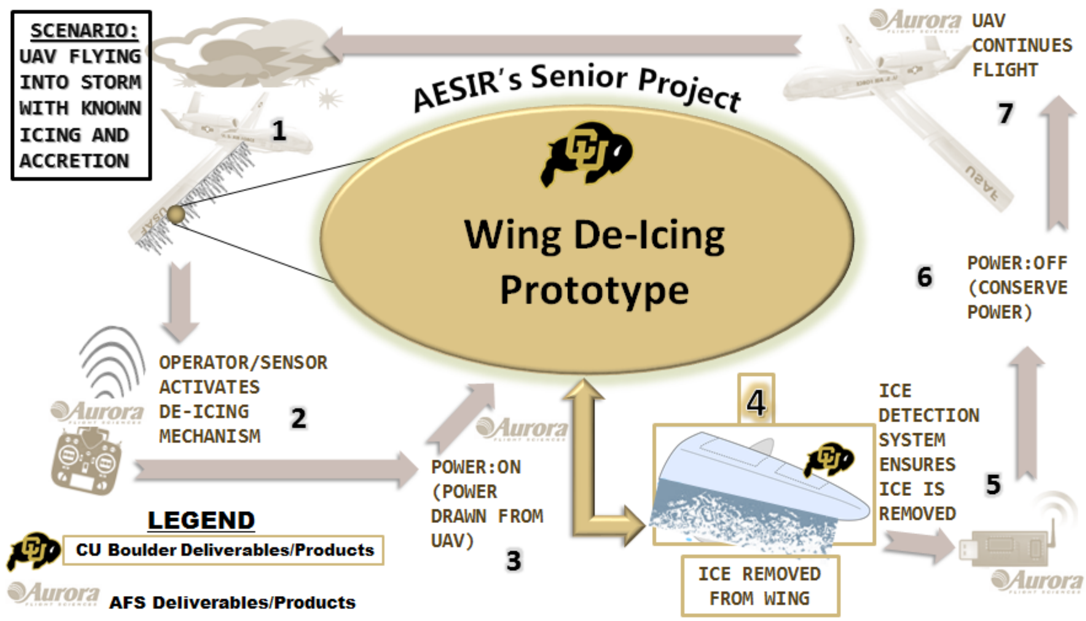


Figure 2. High-level conops

Within the figure, anything that is in black and white with an Aurora logo next to it, are the deliverables/products that Aurora Flight Sciences is responsible for. Items that are in gold or enclosed in a gold boundary are the deliverables/products that the senior project team is in charge of delivering.

2.4 Functional Block Diagram

The Functional Block Diagram (FBD), as shown in Fig. (3), is divided into two major sections: on the left is hardware that is not housed on, or in, the test section and the right-hand side represents all sections to be integrated to the test section. Due to the importance of testing in this project, the test sensors and hardware are incorporated in the FBD.

The sensor suite will consist of temperature, pressure, thickness, and motion sensors. Thermocouples will be placed on the mechanism and test section to read temperature; this data will be fed back to a NI USB 9123 DAQ (which is composed of the NI USB 9162 & NI 9213 components). The temperature DAQ has 16 analog channels with a high speed sample rate of 75 S/s. Exact number and location of the thermocouples will be determined depending on the design and sensitivity of the mechanism components; the sensors will also be placed on the leading edge of the test section and on the outside of ice to monitor the ice temperature. The LabView for temperature data is adjustable but will use sequential sampling at 10 Hz. For testing done within the environmental chamber, humidity will be set using the chamber.

Pressure sensors may also be incorporated on the test section to gather data during device activation. This data will run through a NI USB-6001 DAQ which has 8 analog channels available. The number of sensors will be selected based on further analysis and design of the de-icing mechanism. Pressure sensor DAQ has 14-bit resolution and a sampling rate of 20 kS/s. To measure the ice thickness and the motion resulting from the actuator, a laser system will be implemented.

For the ice thickness measurement a laser pointer and the detector, Thorlabs S302C, will suffice with a sensitivity of 315.82 mV/W. For measuring the movement of the surface caused by the electromagnetic system, a laser pointer may be used for low frequencies and amplitudes or the 500mW Coherent DPSS 532 Laser for high frequencies and amplitudes. The same detection system will be utilized; the detection unit interfaces with a PC computer. This suite of sensors represents readily available and integrable devices for the testing setup. The FBD shows the connections and locations of these system portions.

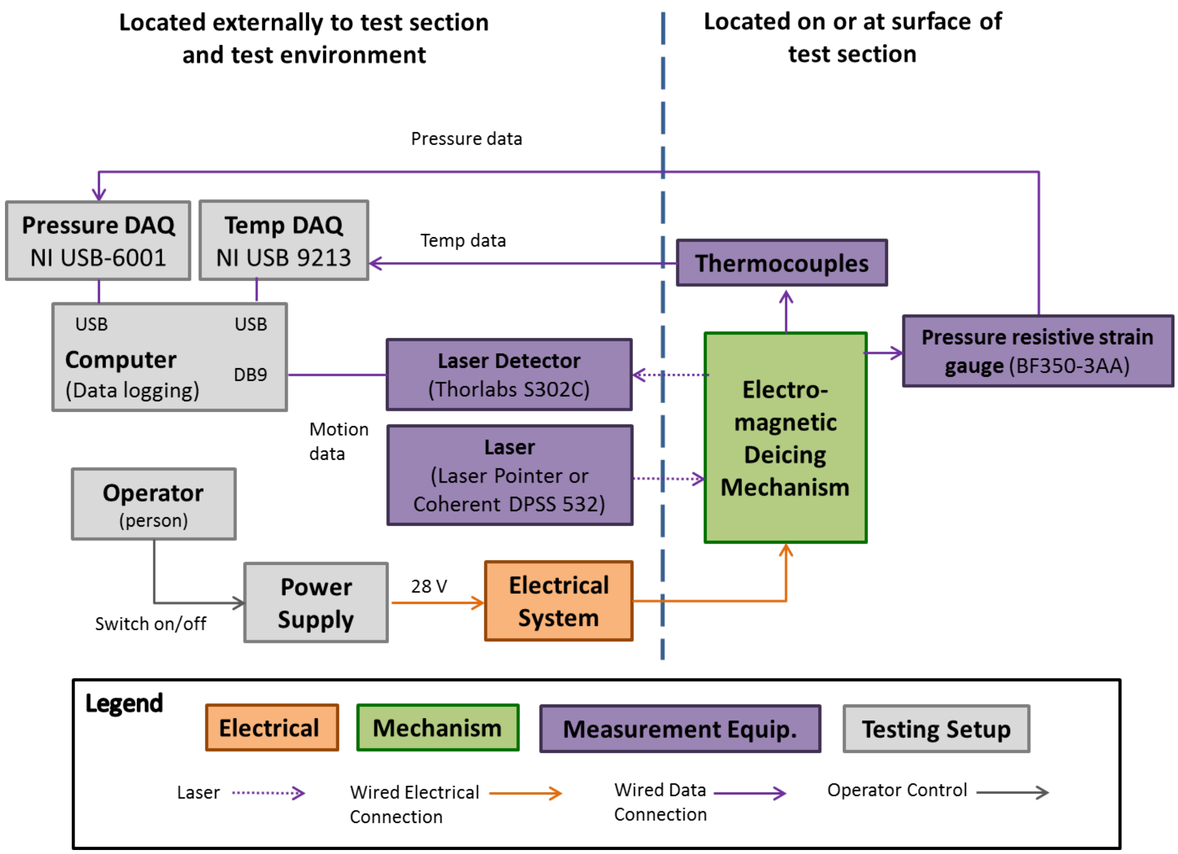


Figure 3. Functional block diagram for de-icing mechanism

2.5 Functional Requirements

The functional requirements for this project are provided by the customer and are shown below. These requirements will serve as parent requirements for the design requirements in section 3.0. In addition these requirements are described using specific terminology depicted below.

Definitions

Prototype = de-icing mechanism + additional components required for functionality

De-icing mechanism = small-scale mechanism(s) that is (are) integrated with the test section for the purpose of removing ice from the wing surface.

Full-Scale System = prototype scaled to full-size Orion in regard to vehicle and mission profiles to be analyzed, but not constructed, by the AESIR Team

Test-Section = small-scale test section whose shape is dependent on the level of testing
- For Level 2 testing, the test section shall consist of a geometric approximation of the leading edge of the DAE11 airfoil.
- For Level 3 testing, the test section shall be a DAE11 airfoil

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.
FR.4 Integration of the de-icing mechanism with the test section shall not decrease the L/D of the test section by more than 10%.

3.0 Design Requirements

The design requirements for this project are derived from customer-given functional requirements as listed in section 2.5.

FR.1 The full-scale system shall be integrable with the Orion UAV.
Verification: Analysis - Use data from prototype testing and scale parameters for full-scale analysis.
Justification: Because the full-scale system is to be integrated with the Orion UAV, the analysis must demonstrate the full-scale system's ability to function within the constraints of the vehicle.

DR.1.1 The full-scale system shall weigh less than 100 lb.
Verification: Analysis - The prototype weight shall be scaled to full-scale based on scaling factors (scale will vary for individual components).
Justification: The customer limited the upper bound of the full-scale system weight; this is to ensure that Orion's performance will not decrease drastically due to a heavier payload.

DR.1.2 The de-icing mechanism shall be integrable with a DAE11 airfoil.
Verification: Inspection. For design purposes, the prototype will be modeled to ensure successful integration. Once integration is complete, the prototype shall be inspected to visually confirm successful integration.
Justification: The DAE11 airfoil closely approximates the wing shape of Orion thus being able to integrate to the specified airfoil demonstrates that the full-scale system could be integrated with the Orion airfoil shape.

DR.1.2.1 The test section chord shall be 18 in.
Verification: Inspection. The chord length will be measured.
Justification: The customer required that the chord length be a minimum of 18 in. The selection of the 18 in. chord offers a broader range of testing environments and decrease material costs.

DR.1.2.2 The internal components of the de-icing mechanism shall fit between the leading edge (0 in.) and half-chord line (9 in.), see Fig. (4).
Verification: Analysis and Inspection. For design purposes, the prototype will be modeled to ensure successful integration in regard to test section's geometry. Once integration is complete, the prototype shall be inspected to visually confirm volume metrics.
Justification: The customer allotted the volume from the leading edge to the half-chord line, which, for an 18 in. chord, results in an available volume from the leading edge to 9 in. from the leading edge.

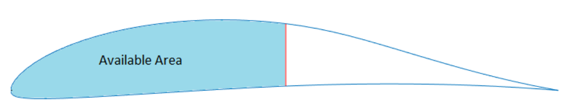


Figure 4. Available cross-sectional area within DAE11 airfoil

DR.1.3 The installation of the system shall not damage or degrade the structural integrity of the wing.
Verification: Analysis and Inspection. Model will analyze stress for any damage to the prototype and test section when the system is not powered on. Inspection will assess for visible damage to the prototype and test section upon installation.
Justification: The installation and activation of the prototype with the test section cannot damage the test section or the prototype, itself.

DR.1.4 The operation of the system shall not damage or degrade the structural integrity of the wing.
Verification: Analysis and Inspection. Model will analyze stress for any damage to the prototype and test section. Inspection will assess for visible damage to the prototype and test section following activation.
Justification: The activation of the prototype with the test section cannot damage the test section or the prototype, itself.

FR.2 The prototype shall remove ice.
Verification: Demonstration. Demonstrating the prototype's ability to remove ice.
Justification: Requirement from customer.

DR.2.1 The prototype shall be capable of removing ice built-up to 0.36 in thick on test section.
Verification: Testing. Just prior to testing, the volume of ice located on the test section will be measured to confirm the correct ice-thickness dimensions on the test section.
Justification: Customer required removal of ice built up to 2% of the chord length.

SPEC.2.1.1 The ice shall cover the test section from the leading edge to 1.26 in. as measured from the leading edge on the upper airfoil surface and 0.54 in. as measured from the leading edge on the lower airfoil surface.
Verification: Inspection. Just prior to testing, the volume of ice located on the test section will be measured via caliper to confirm the correct dimensions (distance from leading edge).
Justification: Customer required ice build-up to span from leading edge to 7% of the chord length on the upper surface, and from the leading edge to 3% of the chord length on the lower surface. These parameters reflect calculations using an 18 in. chord length.

DR.2.2 The prototype shall be capable of removing ice at any time during a five-day continuous flight.
Verification: Analysis. Modeling the degradation of the system in non-icing flight conditions (at cruising altitude and cruising speed) will determine whether the system can withstand this duration in these flight conditions.
Justification: The Orion UAV is a long-duration flight aircraft. Such a UAV requires a compatible system to endure the same flight time.

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.
Verification: Testing. The thickness on the test section will be measured to confirm requirement.

Justification: Requirement from customer. According to the customer, this thickness is the minimum thickness at which the prototype will be activated for ice-removal.

FR.3 The full-scale system shall use less than 4kW-hr to de-ice the wing section.
Verification: demonstration and analysis
Justification: Requirement from customer

DR.3.1 The prototype shall operate on an incoming 28 V DC voltage line.
Verification: Inspection. Use voltmeter to measure incoming voltage.
Justification: The power from the Orion UAV will be provided at 28 V DC thus the prototype must be compatible with this incoming voltage.

DR.3.2 The full-scale system instantaneous power draw shall be at most 2 kW.
Verification: Analysis and Test. Energy consumption model will analyze prototype power requirements and scale to full-scale to ensure full-scale model does not exceed this power draw. Testing will confirm power consumption via power supply.
Justification: Requirement from customer.

FR.4 Integration of the de-icing mechanism with the test section shall not decrease the L/D of the test section by more than 10%.
Verification: Analysis. Because of resource availability for this project, the airfoil profile of the test section shall be modeled to ensure efficiency is not compromised.
Justification: Requirement from customer.

4.0 Key Design Options Considered

For considering key design options, only the de-icing mechanism itself is considered with multiple in-depth analyses and trade studies. For the scope of this project, another key area to consider is testing environment; although this is a critical project element, the lesser depth of analysis for deciding this environment does not warrant a trade study due to extremely limited resources and thus will not be considered in key design options. Thus, this section only introduces the diverse methods of ice-removal systems. To properly assess the prominent solution, a pros and cons table was devised for each mechanism. The mechanism must cater to the requirements in Section 3.0.

4.1 Electro-Magnetic De-icing Mechanism

The Electro-Impulse De-Icing (EIDI) system shown in Fig. (5) is a very effective method of removing ice. The NASA Lewis Research center has performed extensive studies on these systems and holds the promise of "…ice removing with very low energy, minimal maintenance, great reliability, and weight and cost competitive."[1]

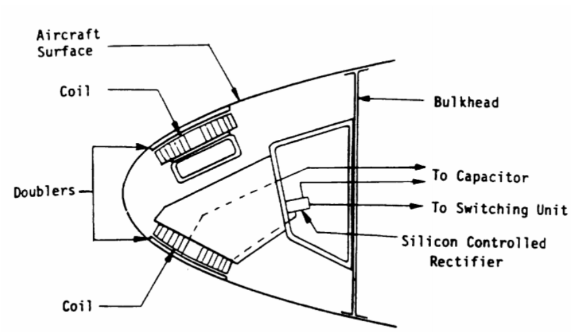


Figure 5. Electromagnetic Impulse De-Icing schematic[1]

The basic and essential principles to this system are electricity and magnetism. The doublers depicted in Fig. (5) consist of a conductive sheet of metal (aluminum) that is mounted between the wing's skin and the solenoid. A capacitor discharges an electrical current through the copper solenoid, giving off an electromagnetic field. A very simplified circuit of the EIDI system is shown in Fig (6).

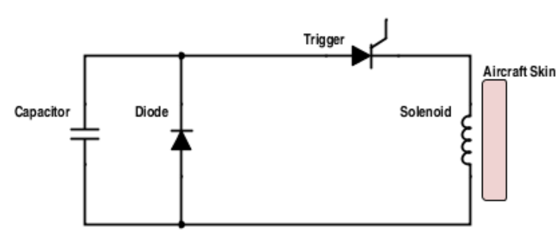


Figure 6. Simplified circuit diagram of EIDI system

A more sophisticated diagram of the EIDI system is shown below in Fig. (7). The change in magnetic field within the solenoid induces an Eddy current that repels the doublers. The magnitude of the force exerted by this induced solenoid is dependent on the number of turns, current, cross-sectional area, and the distance between the conductive metal and solenoid. This repulsion has a huge acceleration and small amplitude that directly strains the wing's skin, effectively shattering the ice accumulated on the wing. The pros and cons for this technique are shown in Table 1.

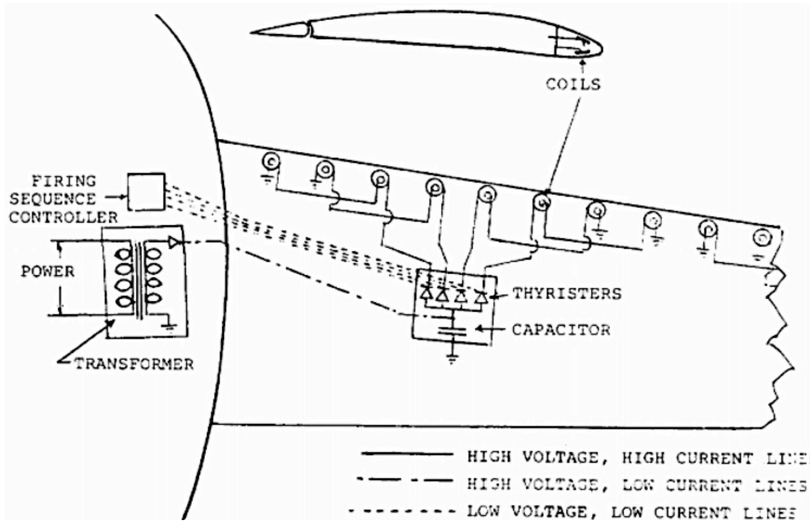


Figure 7. In-depth diagram of EIDI within the airfoil[1]

Table 1. Pros and cons for electro-magnetic de-icing mechanism

Pros	Cons
No impact on L/D	Causes eventual structural fatigue on the UAV wing[1]
Very power efficient	Magnetic interference with radio and communication[1]
Inexpensive	Requires complex structural analysis
Been used previously on aircraft	

4.2 Thermo-Electric De-Icing Mechanism

Thermo-electric de-icing systems are a broad category of de-icing systems that use electrical current to melt ice by resistive heating. They are highly customizable and are used in many applications. Thermo-electric de-icing systems are already used in aviation (shown in Fig. (8)), often in conjunction with other methods such as electro-mechanical. In addition, the heat transfer schematic for this mechanism is shown in Fig. (9).

Figure 8. Thermo-electric heating elements implemented on general aviation aircraft.[2]

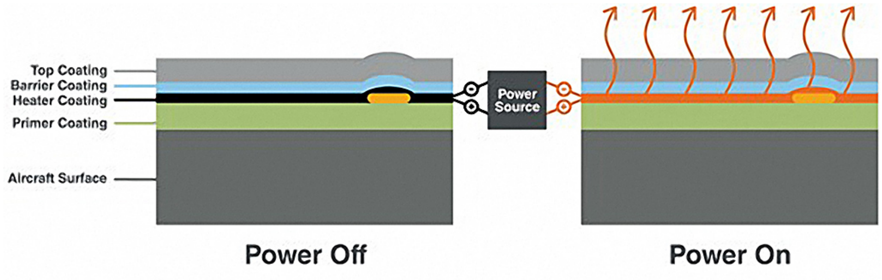


Figure 9. Heat transfer schematic for thermo-electric de-icing mechanism.[32]

The benefits of thermo-electric de-icing systems include ready availability and easy implementation. They are very simple; at the most basic level, they are about as complicated as a light switch. These systems are also capable of varying de-icing capability, meaning they can scale to the severity of the icing conditions. Also, as long as electrical power is available, the system is capable of de-icing for the duration of the flight. Due to their simplicity and availability, they are also inexpensive and require minimal to no changes to the interior of the wing. In turn, the system consists mostly of a thin sheet of thermal elements on the surface of the wing. These thin sheets are very light and can be applied to the existing structure, so thermo-electric systems are very light and retrofitable.

Despite their many benefits, thermo-electric de-icing systems have one major drawback; they consume large amounts of power. For the large surface area of Orion, it may be very difficult to create a thermo-electric system that operates within the 2 kW power range. Another fairly serious problem is the potential for ice to reform farther back on the wing after melting.[33] In order to mitigate the chances of this; the system must operate at fairly high temperatures. Unfortunately, the high temperatures bring about another problem: the Orion has a carbon fiber composite that uses a 250°F resin that could become damaged from heat. These pros and cons are shown in Table 2.

Table 2. Pros and cons for thermo-electric de-icing mechanism

Pros	Cons
Little to no impact on L/D	High Power Consumption
Lightweight	Possibility of ice reforming
Inexpensive	Possibility of overheating composite material
Simple	
Variable icing capability	
Easily implemented and retrofitable	

4.3 Chemical De-Icing Mechanism

Chemical de-icing systems remove ice by applying a fluid over the surface of the wing, which lowers the freezing point of the resulting ice/chemical solution. The general schematic consists of a pump and flow controller which delivers the fluid from a reservoir to the wings via plastic tubes, as shown in Fig. (10). Once at the wings, the fluid seeps through a mesh titanium plate located on a small portion around the leading edge of the wing. The fluid not only de-ices the leading edge but runs back over most of the wing providing good de-icing coverage.[4] The high level overview for this solution is shown in Fig. (11).

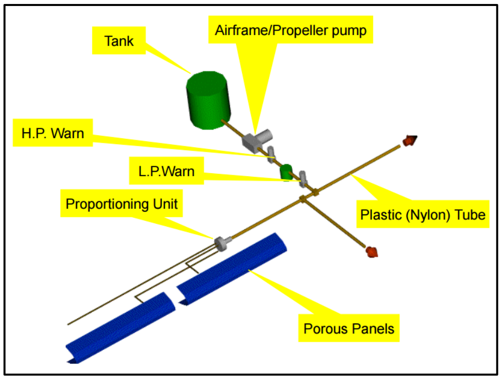


Figure 10. TKS De-Icing Schematic[3]

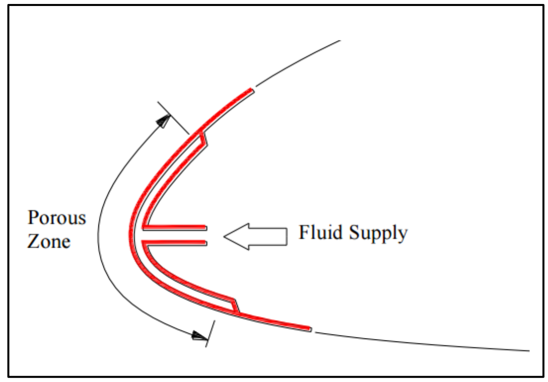


Figure 11. TKS Leading Edge Close-up[3]

This system is currently being used on many general aviation aircraft and is reported to perform well. The main draw for this system is that it is reliable if there is enough fluid left in the reservoir. However, the fluid is very heavy (9.2 lb/gal)[4] and given that the span of Orion is 132 ft it would require a significant amount of fluid to be carried to get a decent amount of de-icing time (200 lb for 3 hours flight time in icing conditions). System pros and cons are shown in Table 3.

Table 3. Pros and cons for chemical de-icing mechanism

Pros	Cons
Method already used on general aviation aircraft. (ex. Older Mooney Bravo)	Has limited amount of deicing battle time. Once chemical runs out, aircraft needs to be out of icing conditions.
Only power required is to operate pump	Chemical must be refilled after each mission where ice was encountered.
Relatively inexpensive to make system, excluding chemical	Chemical used can be expensive when used on full-scale aircraft.
One moving part – the pump	Heavy – weight of system depends on how much chemical needs to be carried

4.4 Passive Anti-Icing Mechanism

Ice phobic coating technique is based on reducing the adhesion force between the wing surface and the ice, preventing ice formation, and repelling small water droplets in the cloud. The ice phobic interaction is lead by chemical or physical properties of materials. The non-polar hydrophobic polymers have chemical properties that are able to disrupt hydrogen bonds between water molecules and non-polar molecules. The physical properties of some materials could create high contact angles between water droplets and the surface that beads up the water on the coating due to the water surface tension as shown in Fig. (12).[6]

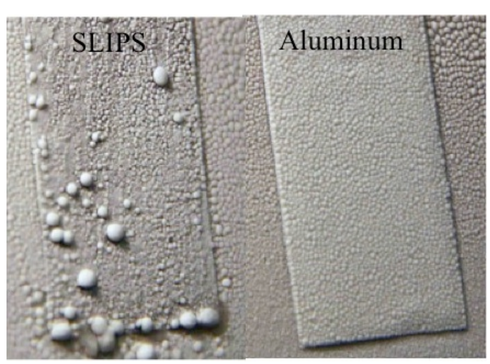


Figure 12. Ice-phobic coating[7]

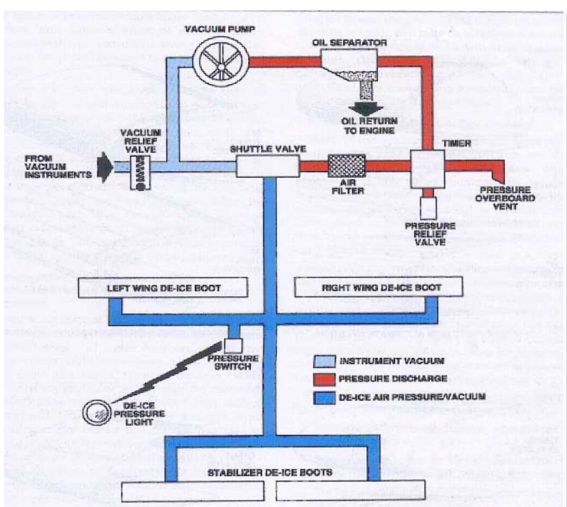
This technique is widely used on many general aircraft. The main advantage for ice phobic coating is no energy consumption during the mission and it is compatible with many materials. However, it becomes porous after a few hours flight especially in severe icing environment, which is not able to reduce ice accumulation any more.[5] It is for this reason that this technique violates requirement DR.2.2 and therefore will not be considered in the trade study. Despite its high efficiency and low mass, any violation of a design requirement immediately excludes the option from the trade study. These pros and cons are shown below in Table 4.

Table 4. Pros and cons for passive anti-icing mechanism

Pros	Cons
Requires no power draw	Is only reliable for the first 8 to 10 hours of flight (violates requirement DR.2.2)
Simple to apply to wing	Expensive to buy chemicals at full scale
Compatible with composite wings	Has to be reapplied after every mission

4.5 Pneumatic De-icing Mechanism

The pneumatic boot system is the most proven ice removal system used on aircraft today. However, this does not imply that it is the most reliable de-icing system used; this technique has just been the most widely used. This type of system is most commonly used on larger twin-engine business aircraft equipped with reciprocating engines, this is due to the fact that the system does not demand the need for an engine that can provide bleed air.[11]



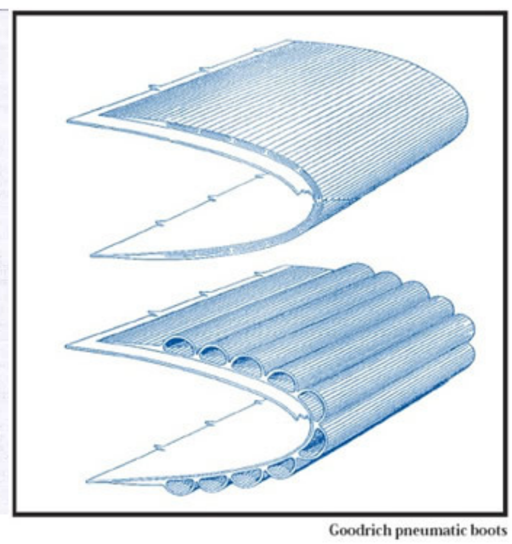


Figure 13. Pneumatic boot system schematic[9] **Figure 14. Pneumatic boot system assembly[10]**

As shown in Fig. (13) the system is composed of one to two vacuum pumps that are tied into the timing gears on the back of each engine. Off of the pumps are two ports, one that sucks air out of the system and another that blows air into the system. These ports have lines that are attached to the rubber boots attached to the leading edge of the wings as shown in Fig. (13). When the system is not in operation, the vacuum pumps are constantly pulling out any air in between the thin layers of rubber making up the boots. This suction helps reduce the externally mounted boots impact on profile drag. Once a sufficient amount of ice has built up on the boots the pilot can activate the system from within the flight station, causing the vacuum pump to rapidly blow air into the boots and inflating them as shown in Fig. (14). The rapid rate of inflation breaks the ice from the surface of the boot and in turn the free stream air flowing around the wing picks up the ice. After a six second cycle, which is composed of going from suction to full inflation and back to being suctioned, the aircraft is clear and the pilot is good to continue normal operation until the ice builds up to an unacceptable level again.[11]

Table 5. Pros and cons for pneumatic boot mechanism

Pros	Cons
Very commonly used system on aircraft	Rubber boots are heavy
Draws very little power	External mounting method has measurable effect on lift over drag ratio
Can be cycled as many times as needed per mission.	Too early of actuation will not remove ice
	Requires the periodic application of a treatment for the rubber and are only predicted to last up to about three years

4.6 Ultrasonic De-Icing Mechanism

The ultrasonic de-icing mechanism represents cutting edge technology in ice removal. Fig. (15) shows a sketch of an ultrasonic deicing mechanism located in the leading edge of an airfoil. Use of ultrasonic devices is well established in other fields thus the actuators which produce ultrasonic waves at a desired frequency are commercially available. Fig. (16) shows an example of an available Piezo Ultrasonic Actuator.

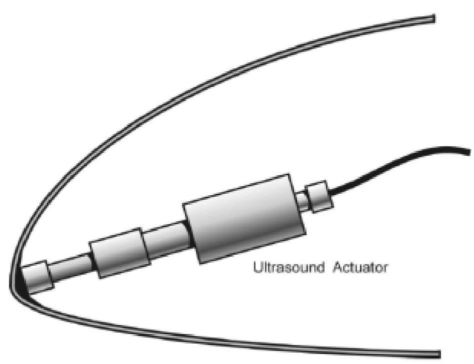


Figure 15. Ultrasonic actuator placed in an airfoil leading edge.[22]

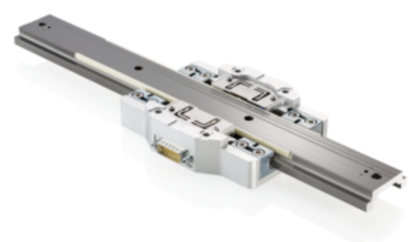


Figure 16. Example of a Piezo Ultrasonic Actuator available from Physik Instrumente.[23]

In terms of the application to de-icing, however, the technology is relatively undeveloped. Research shows the method as successful in removing thin layers of ice; studies have tested up to 3.8 mm (0.15 in.) of ice removal but interestingly the ultrasonic actuators also deter ice formation when tested in icing wind tunnels.[24] All testing conducted so far occurred with preformed or wind tunnel ice and the technology has yet to be applied in a full-scale scenario. As the technology has not undergone flight testing and does not have flight heritage at this point, the full capabilities or limitations of the method are unknown; however, from preliminary research, the ultrasonic deicing technique appears highly effective with little power cost, no L/D impacts, and easy integration. The method is being researched and designs patented in relation to removing ice from fixed-wings[22], rotary blades[25], turbines[26], windshields, transmission wires[27], and other structures.

The device works by breaking the bond or deterring a bond from forming between the ice and surface. To remove an ice accretion, the actuator sends ultrasonic waves through the iced material, which result in a high shear stress at the surface. This stress breaks the bonds between the ice and material thus allowing the ice to fall away. Used as an ice deterrent, the ultrasonic devices are continuously actuated or pulsed creating the surface stresses which stop ice from bonding to the material. Fig. (17) shows a testing image where ice buildup is deterred in the vicinity of the actuators. Predominately research has focused on metal surfaces but glass and composites have also been tested.[26]

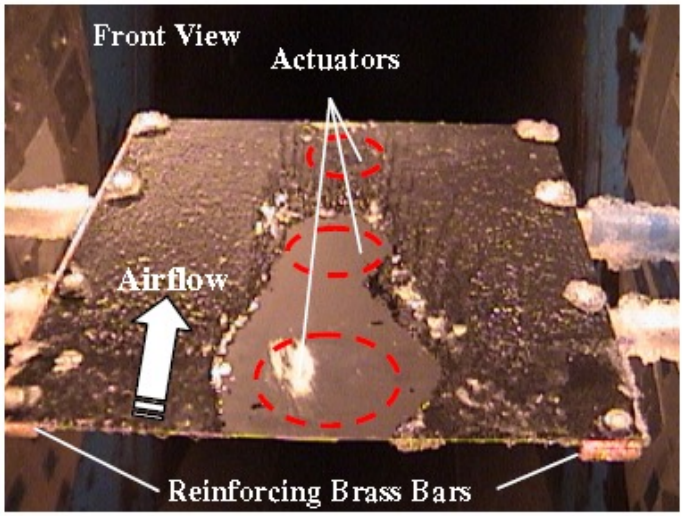


Figure 17. Ultrasonic actuators as an ice deterrent.[24]

Table 6. Pros and cons for ultrasonic de-icing mechanism

Pros	Cons
No impact on L/D	Extensive lab research but no flight heritage or full implementation
Very power efficient. The actuators require low power and are efficient.	Full extent of capabilities unknown
Ultrasonic actuators are commercially available at low cost	
Cutting edge, potentially a new method not yet on the market	

5.0 Trade Study Process and Results

This section shows the comprehensive analysis for the weighted trade study. To begin, major design criteria were carefully selected as well as relative weights (explained in Table 7). After the criteria were properly evaluated, the normalized scaling values were then assigned to rank the mechanisms. Using this scale, the ranking values were chosen for each criterion in regard to each de-icing technique via inspection, documented research, and back-of-the-envelope calculations. Finally, the weighted trade study was completed and is shown below in Table 8.

5.1 Design Criteria

Table 7 shows each design criteria considered during the trade studies as well as their relative weights. In addition, the scaling for these criteria is shown in Table 8 as well as the criteria explained in section 5.2.

Table 7. Criteria weighting explanations

Criteria	Weight	Explanation
Energy Consumption	30%	Since some designs use a high power draw for only an instant of time and others draw power for an extended period of time and the system is run off of two 28 volt batteries, it was decided that energy consumption (explained in section 5.2 of this report) would be a better parameter than power draw. This way the playing field is more level and we can ensure our system will not damage the battery by trying to pull more amperage than what the battery can handle. Aurora Flight Sciences stated their highest deliverable to be a functional low power system. Under the assumption that all of these methods can be made functional, energy consumption was weighted the heaviest.
Weight	25%	Aurora Flight Sciences stated they wanted the system to be as light as feasibly possible. So the need for a weight parameter immediately following the energy parameter was imperative.
TRL	20%	This weight was based off of how easy it would be to make the system functional. If the design has very little documentation on it or has never been tested on an aircraft before then it may be out of the scope of our project.
Difficulty/ Manufacturing	15%	This was considered to be a level of "hassle" criteria. Even if there is sufficient documentation on the product, needing high levels of manufacturing skill or abilities to find materials to build it then the design would fall out of the scope of this project.
Cost	10%	Aurora Fight Sciences never stated a budget to be within at full scale. This was weighed the least because the AESIR team only requires the cost of the test section to be within the $5000 budget and when most of the systems considered are scaled down to the size of the test section the cost is manageable and therefore not a big concern.

Table 8. Normalized values for each criterion

Normalized Value	10	9	8	7	6	5	4	3	2	1
Energy Occupancy [%]	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
Weight [lb/ft]	0-0.15	0.15-0.3	0.3-0.45	0.45-0.6	0.6-0.75	0.75-0.9	0.9-1.05	1.05-1.2	1.2-1.35	1.35-1.5
Technology Readiness Level	10	9	8	7	6	5	4	3	2	1
Difficulty/ Complexity	None	Almost none	Very little	Little	Some	Good bit	A lot	Too much	Way too much	Not Possible
Cost [$USD]	0-400	400-800	800-1200	1200-1600	1600-2000	2000-2400	2400-2800	2800-3200	3200-3600	3600-4000

5.2 Criteria Scaling

Energy Occupancy: This scale was developed to provide an appropriate energy consumption measurement that was able to balance the lack of the scale defined as power consumption. Since some deicing mechanisms, for example, electromagnetic pulses, required huge amount of power but only for a few seconds, the scale in unit of energy shall be more reliable. However, there was no energy standard to compare with, therefore, a new parameter was introduced; Energy Occupancy, q, which is the ratio between effective energy consumption by each method, E_{eff}, and energy requirement limited to 2 kW power over 2 hours of flight, E_{total}. Assuming that each mechanism was able to completely remove the ice on the wing under the same environmental condition with N times within 2 hours, the working cycle, $t_{cycle,}$ was defined as the time between activation of the system and stop. The time for ice accumulation to maximum ice thickness (d), 0.36 in., $t_{gap,}$ was 432s based on the worst moderate ice accumulation rate 3 inch per hour (no aircraft is approved for flight in severe icing conditions). This is demonstrated in Fig. (18), which shows the working cycle for each method. In Fig. (17), d is the thickness of ice originally on the wing at one instant (no more than 0.36 inches). tcycle is the deicing time for each method, and tgap is the time for ice accumulation on the wing again. Using these variables, the effective energy and energy occupancy can be calculated with Eq. (1) and Eq. (2).

$$E_{eff} = P_{method} * t_{cycle} * N = P_{battery} * (t_{total} - N * t_{gap}) \tag{1}$$

$$q = \frac{E_{eff}}{E_{total}} = \frac{1}{1+\frac{P_{battery}*t_{gap}}{P_{method}*t_{cycle}}} \tag{2}$$

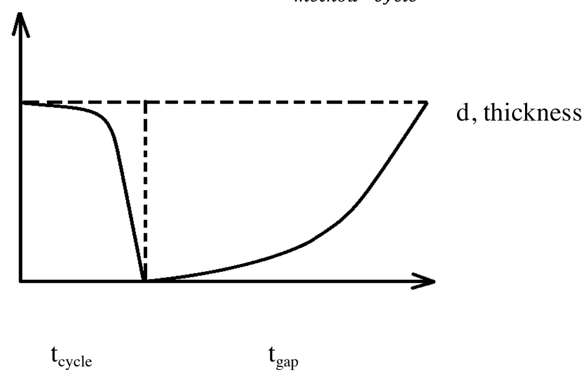


Figure 18. Working cycle applicable to each de-icing method

Weight: The maximum weight was set by the heaviest method, which was found to be a chemical system. A weight of a currently implemented chemical de-icing system was interpolated to find the weight per foot span. A TKS Ice Protection System is being used on the Beechcraft A36.[1] It holds 50.6 lb. of de-ice fluid and has a span of 33.5 ft. This results in a weight per span of 1.51 lb/ft. Analysis of another implemented chemical system confirmed this number.

Technology Readiness Level (TRL): The TRL levels used were defined by NASA in the document "Definition Of Technology Readiness Levels".[30] As the paper defines a scale from 1-9, a new level 1 was created and the existing levels were shifted up. The levels are outlined as follows:

1. Never before reported
2. Basic principles observed and reported
3. Technology concept and/or application formulated
4. Analytical and experimental critical function and/or characteristic proof-of concept
5. Component/subsystem validation in laboratory environment
6. System/subsystem/component validation in relevant environment
7. System/subsystem model or prototyping demonstration in a relevant end-to-end environment
8. System prototyping demonstration in an operational environment
9. Actual system completed and "mission qualified" through test and demonstration in an operational environment
10. Actual system "mission proven" through successful mission operations

Difficulty & Complexity: This scale was developed by James Voss in his "Trade Studies" presentation for ASEN 3036: Introduction to Human Spaceflight.[31] Originally it was a measure of the hassle involved in various transportation methods. Much like hassle, the Difficulty/Complexity metric is aimed at measuring the feasibility of the method given the resources available to the team. Since this is hard to do quantitatively, Colonel Voss's qualitative scale was adopted.

Cost: The cost scale was based on a maximum of $4,000. This number was chosen as the total project budget of $5,000 minus a buffer of $1,000 that can be used for travel or other unforeseen costs.

5.3 Trade Study Values Assigned for Each Method

5.3.1 Electro-Magnetic De-icing Mechanism Trade Study

Energy Occupancy – 7
Using Eq. (2) the energy occupancy percentage came out to be 33%. This value was based on a power consumption of 439.4 W/ft., where the total time to de-ice was 1 second. The gap time was 59 seconds, based on a 60 second cycle.

Weight – 8
The entire EIDI system, including coils, wires, and electrical components has a pessimistic weight of 7 ounces (0.44 lb.) per ft. span.[1] Based on the scale in Table 8, this weight ranks at an 8.

TRL - 8
As mentioned before, NASA's Lewis Research center for de-icing has does an extensive study on the EIDI system. This system has been successfully demonstrated and tested in an icing wind tunnel. The EIDI system was also implemented on aircraft during successful flight tests in icing conditions. Successful meaning the ice was completely removed from the wing. The only reason the EIDI system ranks an 8 instead of a 9 is it has not been implemented on a UAV.

Difficulty & Complexity – 5
This criterion was more subjective and was assessed as a 5. This was because the system involves electrical components that require meticulous modeling and positioning (within the wing composite). The EIDI system will cause structural fatigue to the wing composite which can be damage materials outside the linearly elastic domain. These strains will have to be considered under demanding structural analysis. Furthermore, strong magnetic fields are infamous for disrupting radio and communication systems. This phenomenon will have to be considered when linking the model to the full-scale Orion.

Cost – 10
Fundamentally, the EIDI system <u>per test section</u> compromises of 4 – 6 solenoids, 4 – 6 capacitors (400-800 μF), wires, a silicon controlled rectifier (SCR) kit and 2 unalloyed aluminum discs.[#] These materials have a pessimistic cost of 200$ depending on the quality of the products. Additionally, these electrical components are readily accessible Labs located at the University of Colorado Boulder, which will significantly decrease the cost of this operation.

5.3.2 Thermo-Electric De-icing Mechanism Trade Study

Energy Consumption – 1
Using Eq. (2) the energy occupancy percentage came out to be 90.3%. This value was based on a power consumption of 2.7 kW/ft. where the total time to de-ice was 9 second. The gap time was 171 seconds, based on a 180 second cycle.

Weight – 8
Thermo-Electric de-icing systems are very light. The most common material used for thermo-electric heating elements is Nichrome, which has a density of 8400 kg/m^3. Assuming a 1 ft section of the DAE 11 airfoil with a 1.5 ft. cord, and the front quarter of the airfoil is cover in resistive heating elements gives a heating surface area of 115.8 in^2. Then assuming this surface area is covered at 25% with a 1 mm layer of Nichrome. This gives a total mass of 0.35 lb/ft.

TRL – 10
Multiple variants and systems exist and are 'mission proven'.

Difficulty & Complexity – 7
The technology is readily available and easily applied to the surface of the airfoil. However, we will likely take a phased de-icing approach with which will likely require a microcontroller. Also, we may need to add a layer of insulation between the resistive elements and the surface to help ensure the surface stays at a safe temperature, and possibly improves efficiency by having less heat transfer into carbon fiber composite.

Cost – 10
Commercial thermo-electric de-icing systems are relatively cheap, but not already designed for a UAV like Orion. However, because the technology is fairly simple we would be able to make etched resistive elements using lithographic techniques greatly reducing cost. Or at really low cost or for prototyping Nichrome wire could be used. Nichrome wire can be purchased in 100ft rolls for about $10.

5.3.3 Chemical De-Icing Mechanism Trade Study

Energy Occupancy – 10
A typical TKS de-icing system on a 33.5 ft wingspan operates at 28 volts and 1.5 amps, which is equal to a power draw of 1.25 W/ft.[19] From observing a video demonstrating the system, it is estimated that a cycle to remove ice takes at most 3 min. (180 sec.)[12] which results in a total energy draw of 225.67 J. Entering these values into Eq. (2) results in an energy occupancy value of q = 3.32%.

Weight – 1:
As stated earlier the chemical system was used to set the maximum weight allowable. A TKS Ice Protection System being used on the Beechcraft A36 was analyzed to calculate the weight per span.[13] The reservoir holds 50.6 lb. of de-ice fluid and the aircraft has a span of 33.5 ft. This results in a weight per span of 1.51 lb/ft. This was confirmed by analyzing another implemented chemical system.

TRL – 10:
The chemical method received the highest possible score of TRL. The requirement states: “actual system ‘mission proven’ through successful mission operations”. Chemical systems are one of the most common forms of de-icing and have reached a level of full integration with operational systems.

Difficulty & Complexity – 5:
Many of the parts required can be easily acquired and assembled such as a tank, pump, and tubing. However, the mesh titanium plate that curves around the leading edge of the wing could be difficult to obtain. Thin (0.7 to 0.9 mm) titanium plates can be bought and could be warped to mold to the leading edge. The difficulty comes with the precision that is required to laser drill 800 holes per square inch, each at 0.0025 in diameter.[21] This could not be done at CU and the plate would have to be sent out each time a new design or size was needed. For this reason, it was scored with a ‘good bit’ of difficulty/complexity.

Cost – 8:
A rough outline of the parts required, with prices, is presented here:
3 gallon tank[14] - $35.70
Tubing (1/2” and 5/16”)[15] - $300
Pump (3 gal/min, 55 psi)[16] – $61.42
Flow controller[17] – $60.88
Titanium sheet (0.8mm X 1000mm X 100mm)[18] - $90
Total - $548

Including a safety factor accounts for extra parts, rush shipping, and other unforeseen costs. Adding an additional $252-$652 would cause the final cost to score an 8.

5.3.4 Pneumatic De-Icing Mechanism Trade Study

Energy Occupancy - 10

Using Eq. (2) the energy occupancy percentage came out to be 1.11%. This value was based on a power consumption of 74.02 J/ft., where the total time to de-ice was 6 seconds. The gap time was 432 seconds, based on an ice thickness of 0.36 inches.

Weight - 1

It was also found that the estimated weight for a pneumatic boot system on a typical twin-engine business aircraft (i.e. a Cessna 421) weighs about 55 lb. for the complete system.[19] Using the same span as the energy section the following equation, Eq. (3), was used to calculate the total weight of the system for a 1 ft. test section. The yielded value from the calculation was 1.35 lb.

$$\text{Weight} = \frac{\text{System Weight}}{41\text{ft}} \tag{3}$$

TRL - 9

Based off of the cited NASA scale and the fact that this system is so common a value of 9 was selected for this criterion.

Difficulty & Complexity - 6

This value was based off of the fact that this system is the most common method of deicing, documentation on installation is abundant and materials are easily found. With these facts taken into consideration and that A&P mechanic team member Andrew Moorman has maintenance experience with the system, a value of 6 was selected.

Cost - 7

A pneumatic boot system to cover about 25% of the wingspan of a Pilatus PC-12 costs about \$5,364.84, where the wingspan of a Pilatus PC-12 was found to be 58ft.[20] With this information the following equation, Eq. (4) was used to estimate the cost for a test section to be \$1,214.00.

$$\text{Cost} = \frac{(\text{System Cost} * 4)}{58\text{ft}} \tag{4}$$

5.3.5 Ultrasonic De-Icing Mechanism Trade Study

Energy Occupancy – 6

The energy usage of the ultrasonic actuators is relatively low using. Values from different experiments vary but estimates seem to show that power is required at about 0.34 W/in^2 to remove 0.02 in. of ice thus an average value is taken.[24]

Weight – 4

A Piezo Ultrasonic Actuator weights about .4 kg (1.1 lb). According to research one actuator can deice an area of roughly 144 in^2 and assuming a square area of de-icing, one actuator could de-ice about 1 ft of wing, this gives a weight of 1.0 lb/ft.[24] This is likely an overestimation but the limits of the actuators are not extensively tested so the estimation here is kept conservative.

TRL - 4

This system has undergone rigorous experimental testing but the method has yet to be applied. This means that while research exists on ultrasonic actuation, there aren't examples of full-scale functional systems as reference.

Difficulty & Complexity – 5

The difficulty and complexity of this system is hard to judge due to the problem of TRL discussed above. The actuators themselves are commercially available and seem relatively easy to work with which decreases the difficulty; however, the complexity of the project increases since there would be an aspect of experimentation to establish a configuration of actuators that works consistently. The lack of implemented examples increases the difficulty and complexity as it leaves more unknown variables to try.

Cost – 9

Small ultrasonic actuators are commercially available at low cost from a variety of vendors. Example prices range between $12 and $100 from the vendor STEMiNC.[29] In a project with more certain knowledge, the cost would be a 10 but to factor in for potentially having to test a few different motors and configurations, the cost factor is lowered to a 9. The trade study value of 9 ranges from $400-$800 which allows for purchasing at least four of the more expensive actuators and retaining roughly $400 for any other project needs.

5.4 Trade Study Results

Using the criteria weights explained above as well as the scoring pertaining to each criterion for each technique, the trade study produced the following results as shown in Table 9. As shown, the electro-magnetic de-icing technique scored highest.

Table 9. Completed trade study for all criteria pertaining to each de-icing mechanism

Criteria	Weight	Electro - Magnetic	Thermo - Electric	Chemical	Pneumatic	Ultrasonic
Energy Occupancy	*30 %*	7	1	10	10	6
Weight	*25 %*	8	8	8	1	4
TRL	*20 %*	8	10	10	10	4
Difficulty & Complexity	*15 %*	5	7	5	4	5
Cost	*10 %*	10	10	8	7	9
TOTAL	***100 %***	**7.45**	**6.35**	**6.8**	**6.55**	**6.05**

6.0 Selection of Baseline Design

Ice accretion can have very detrimental effects on aircraft during flight. It is important to combat the ice in a very power, weight, and aerodynamically efficient manner. The six diverse de-icing methods explored in the trade study have very distinct advantages/disadvantages that were ruled out.

The passive de-icing system potentially could have scored the highest rankings. This system requires no power, has minimal effects on drag, simple to apply, and has been frequently used on many aircraft; however, this system fails to directly adhere to the DR.2.2 design requirement. The ice-phobic coating needs to be constantly reapplied after 8-10 hours of flight; it simply cannot withstand Orion’s lengthy flight time. Additionally, at Orion’s full scale, this coating would be very expensive. This design option was considered, but ruled out in the pros and cons section before the trade study.

The next de-icing system eliminated from the trade study analysis was the ultrasonic method. This fascinating method of removing ice is very experimental. Since it has never been implemented on an aircraft, it was heavily penalized on the TRL scale. This complex system also requires a pervasive vibration and resonance analysis. Resonating structures can be highly destructive to nearby aircraft elements (hardware and electronics). Furthermore, the purely experimental research makes it difficult to judge how effective and efficient the method will truly be once implemented.

The next lowest scoring de-icing system eliminated from the trade study was the thermo-electric method. One of the primary design requirements is a power-efficient system. This frequently used method is very power intensive. As a result, the thermo-electric mechanism was heavily penalized because energy occupancy had the greatest weighting.

The pneumatic system also scored low in the trade study. This mechanism fails in the weight category, ranking at 1. Since weight is a huge design factor, the pneumatic boots were rebuked. Also, the pneumatic boots are infamous for not completely removing ice if actuation is done too early. Furthermore, this mechanism is external to the wing, impacting the lift-to-drag ratio.

The chemical de-icing system was the secondary contender for a final design choice. The chemical de-icing system involves drilling into the composite wing. Manufacturing these tiny porous holes involves very delicate and expensive machinery. Also, carrying massive fluid tanks will be heavy and volume intensive for extensive mission durations. Testing these chemical systems would be potentially hazardous.

At last, the prevalent de-icing mechanism of the trade study analysis is the electro-magnetic system. With a total ranking of 7.45, this system is power and weight efficient. Additionally, it has an extensive heritage consisting of: electrodynamics studies and tests, structural studies, fabrication techniques, flight and icing tunnel tests.[1] This complex system will certainly not be easy to manufacture, implement, test, and scale, but represents a balance between cutting-edge technology and the existing methods. Upon successful completion of this project, the electro-magnetic system will be effective in removing ice. The general approach and feasibility to successfully complete this project will have the following process.

To ensure feasibility, the method has been considered from a variety of aspects including manufacturing, integration, and testing. The first step will be to finalize the design, which will include a model of the structure and power consumption. Since the design is internal to the wing, L/D will not be impacted removing the need for modeling. As manufacturing progresses, concurrently testing will be conducted to practice the ice application technique of casting. Initial testing on the device will include measuring the force exerted by the system as well as aliveness testing and power consumption testing will meet level one objectives. Integration and testing of the implemented prototype consists of the next major mile marker. Using a test section that is a geometrical approximation of the airfoil will reduce manufacturing difficulty while still allowing for valuable data gathering. This test section will be iced using the previously developed techniques and tested to insure full functionality of deicing. By completing such testing, the design will be verified to capable of being integrated and of ice removal. The final step is to integrate the design to the DAE11 airfoil, which will prove out the design for the specific case. This testing flow is meant to build up the accuracy of results, first covering low-level functionality before progressing to more precise testing. The electro-magnetic prototype may be fully proved out and is within the capabilities of team and scope of the project duration.

Based on the trade study, an electro-magnetic solution balances the design considerations without violating any of the requirements. Furthermore the aspects of manufacturing, integration, and testing of this solution are manageable. The engineering students of the AESIR team are excited and passionate to take on this project, and hopefully revolutionize the way UAV's are deiced.

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