Performance of a Freezing Point Depressant System in Appendix O Environment

OVERVIEW

- Background
- Freezing Point Depressant (FPD) Panel Design
- Predictive Analysis
- Performance in Appendix O
- Certification Considerations
- Possible Certification Ice Shapes
- Icing Wind Tunnel Tests
- Conclusions and Future Work

Background

- CAV currently designs FPD systems to perform as an anti-ice system in continuous maximum clouds and a de-ice system during intermittent maximum encounters.
- Using guidance from AC23-1419-2D, current tank is sized based on flow required for operating in the continuous maximum environment.
- Rule making currently in progress to determine certification requirements for Part 23 in freezing drizzle and freezing rain (Appendix O).
- Goal of exercise is to determine performance of FPD system in appendix O and how it may effect future system designs.

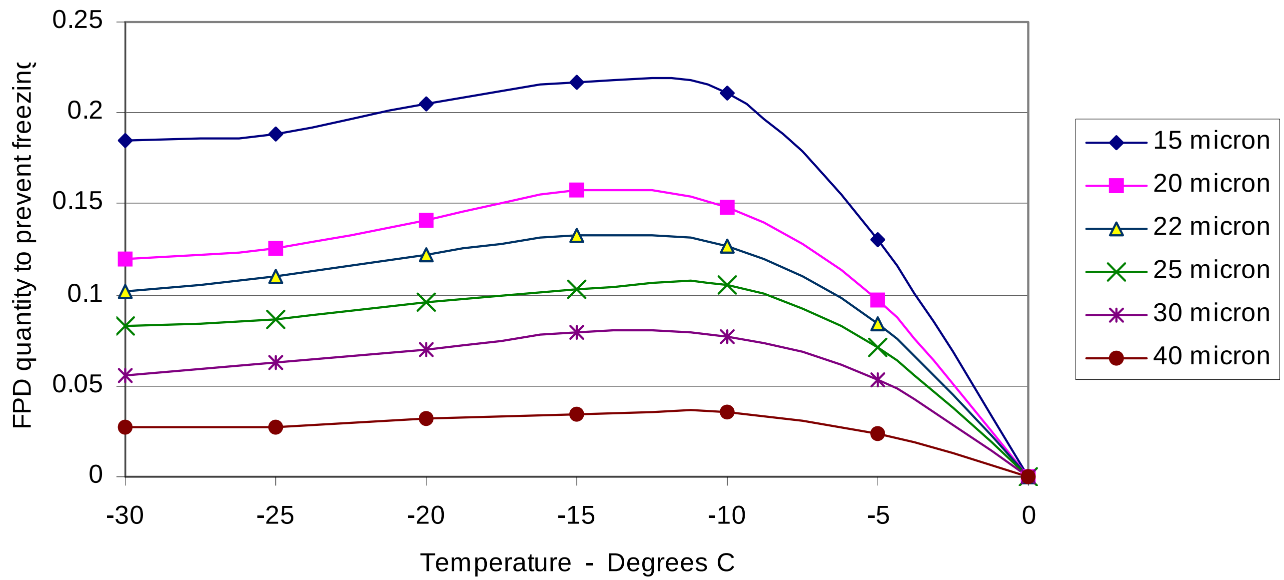
FPD Panel Design

- **Define aircraft geometry and performance parameters**
  - **For this analysis a generic wing panel and tail panel was defined**
  - **Similar geometry and performance parameters to recent programs**
    - **Wing represented by NASA NLF airfoil (NASA LS(1)0417-MOD)**
      - **Cruise AOA of -2.2**
      - **Climb AOA of 2.2**
      - **1.0m at tip of panel, 1.25m at root of panel**
    - **Tail represented by NACA 0012 airfoil**
      - **Cruise AOA of -2.0**
      - **Climb AOA of 0.0**
      - **0.75m at tip of panel, 1.0m at root of panel**
    - **TAS of 110 m/s during cruise at 22,000ft**
    - **TAS of 75 m/s during climb at 22,000ft**

FPD Panel Design

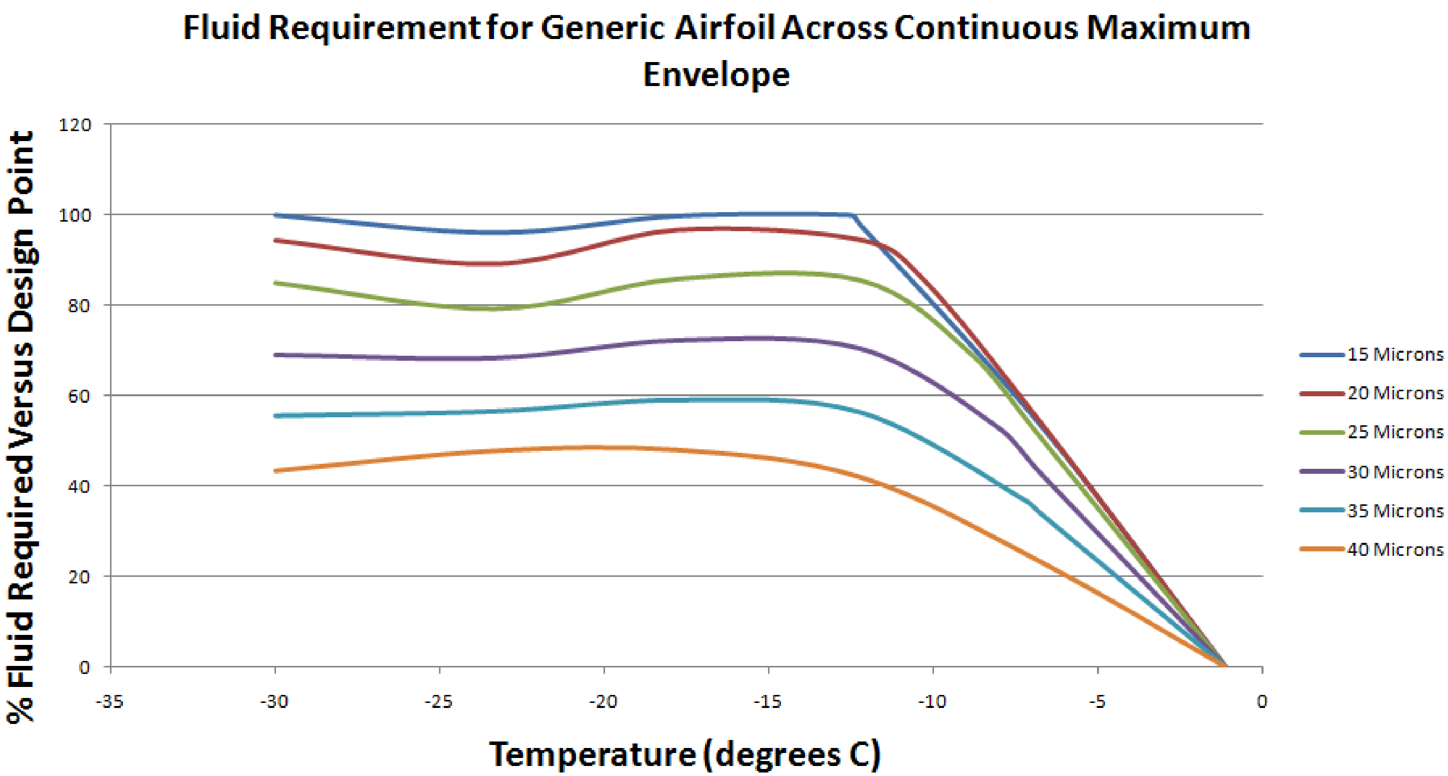
- **Define design point using Appendix C envelope and mass fraction curve of FPD fluid**

FDP Liquid required to prevent freezing.
(Unity catch efficiency)



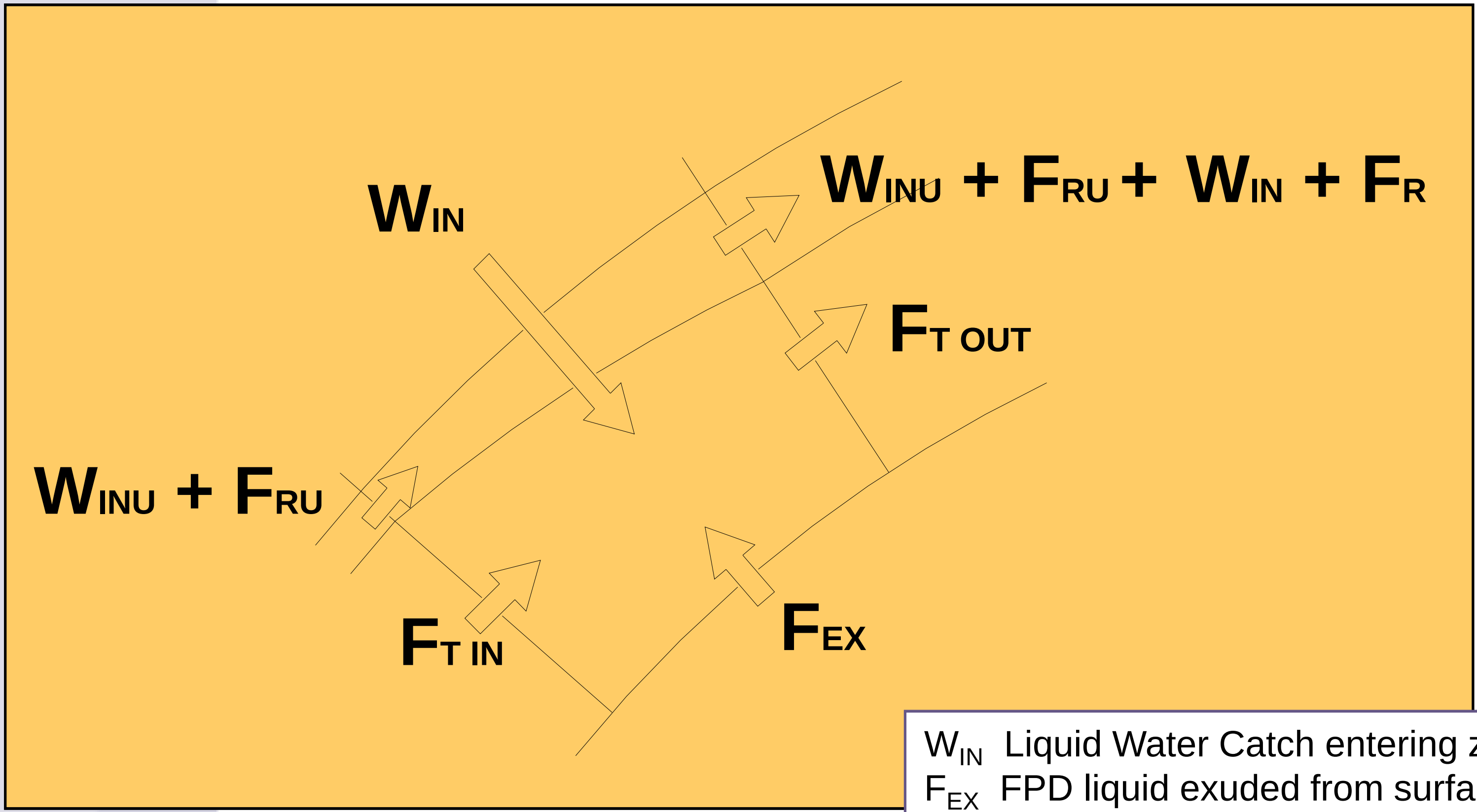
FPD Panel Design

- Study done on an airfoil were collection efficiency various over the surface and varies with droplet size
- Results verify the use of the design temperature and droplet size



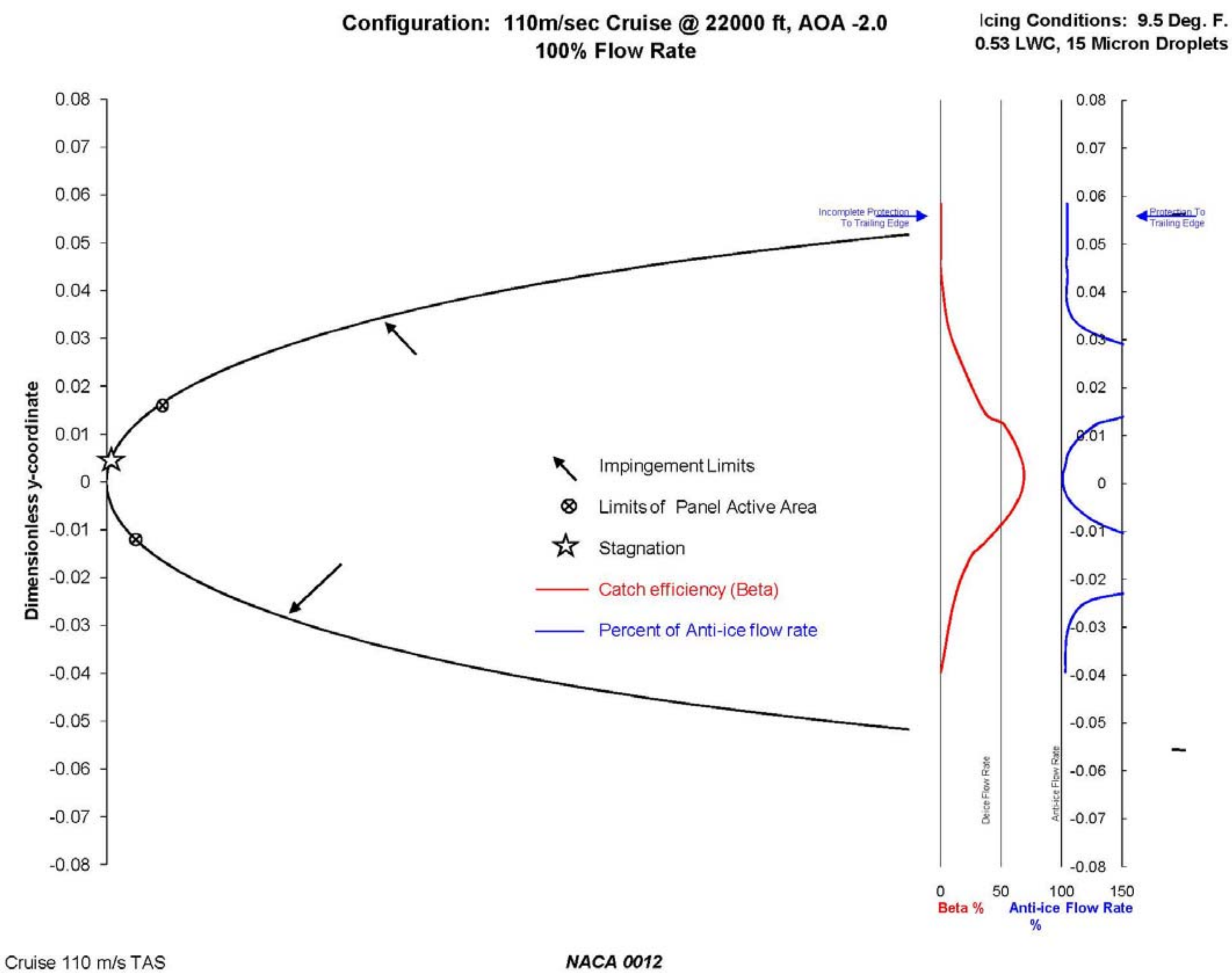
FPD Panel Design

- **Use FPD analysis tool and LEWICE output to define panel flow rate and size**



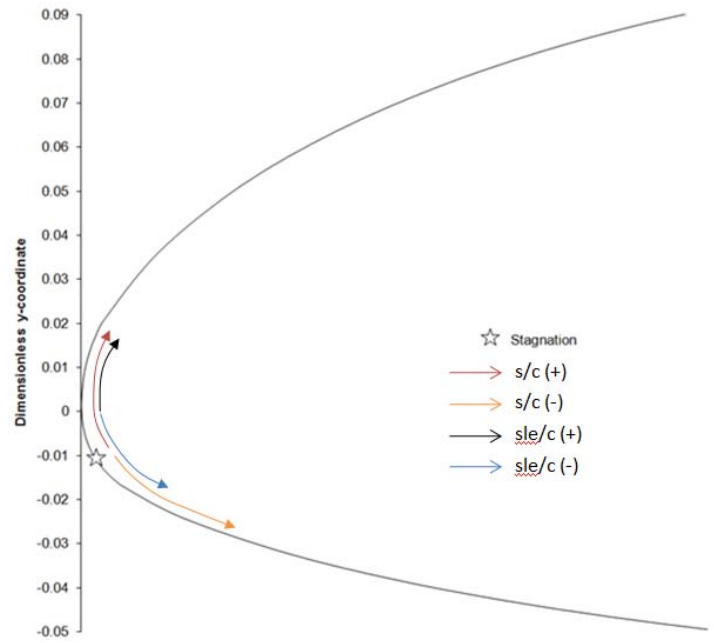
W_{IN} Liquid Water Catch entering zone
F_{EX} FPD liquid exuded from surface into zone
F_R FDP liquid required to maintain W_{IN} liquid
F_T Excess fluid transferred downstream
W_{INU} Liquid Water Catch from upstream zones
F_{RU} FPD liquid required to maintain W_{INU} liquid.

FPD Panel Design



FPD Panel Design

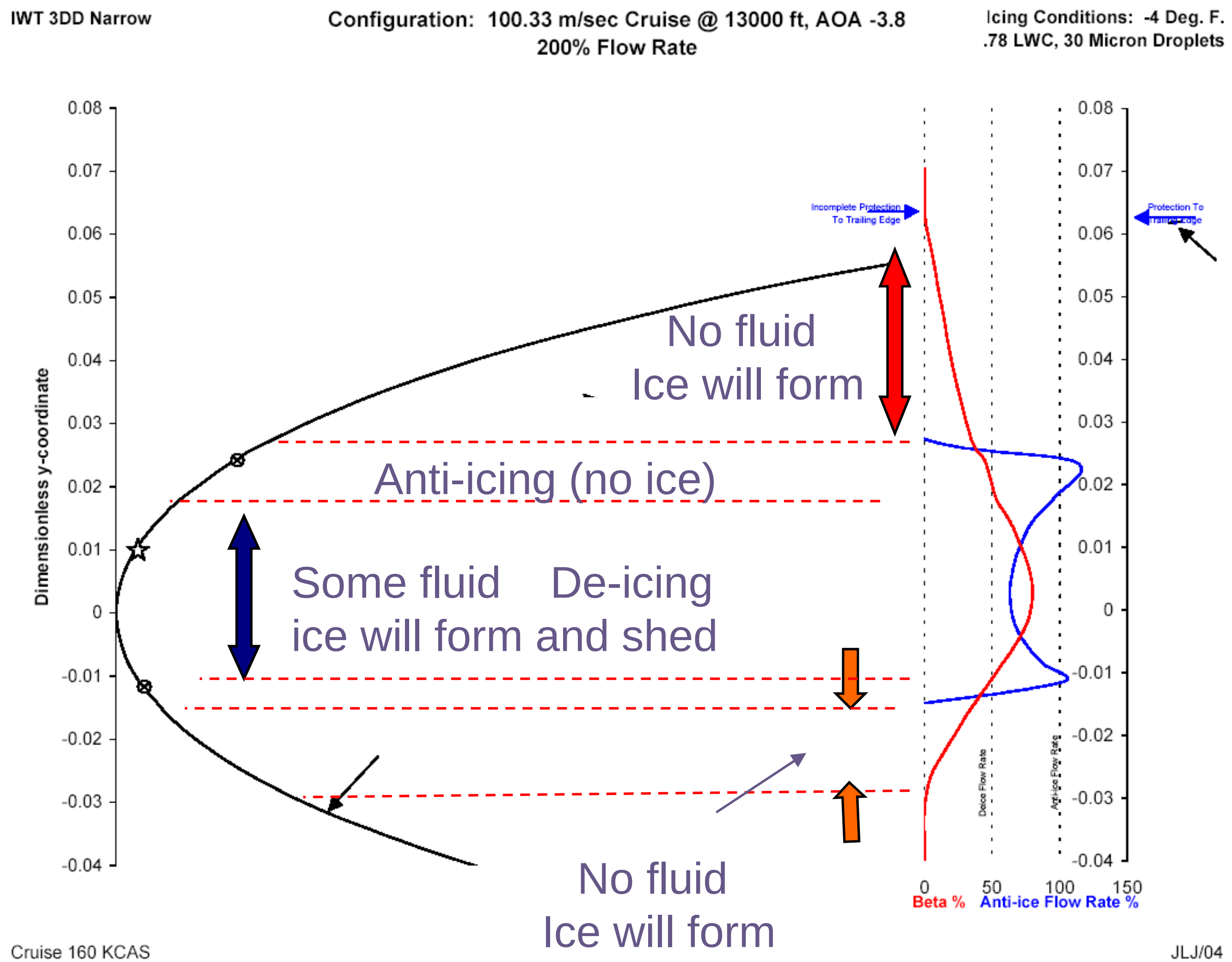
- **Design Results**
  - **Wing AOA -2.2 to 2.2**
  - **Wing 1m at tip, 1.25m at root**
  - **Tail AOA -2.0 to 0.0**
  - **Tail 0.75m at tip, 1m at root**



	Tip sle (cm)	Tip sle(-) (cm)	Tip sle(+) (cm)	Root sle (cm)	Root sle(-) (cm)	Root sle(+) (cm)	Panel flow rate (ml/min/cm^2)
Wing	6.271	2.549	3.722	6.544	2.816	3.728	0.059
Tail	3.304	1.088	2.216	3.733	1.247	2.486	0.079

Predictive Analysis

- **With defined panel FPD tool can be used to predict performance**



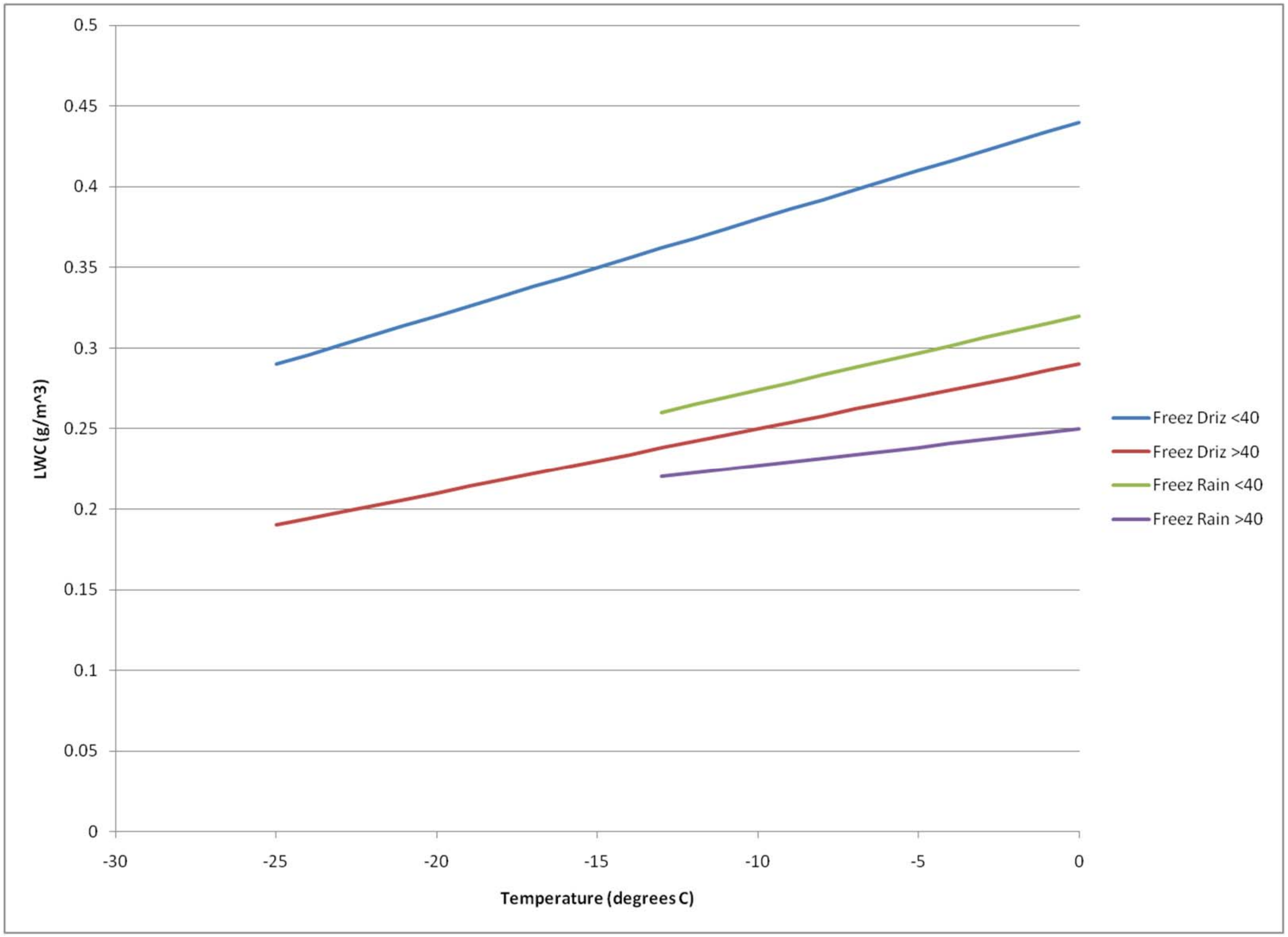
Predictive Analysis

- **0.8 Minutes of Operation**

Performance in Appendix O

- Evaluated using predictive analysis previously described.
- System designed for Appendix C performance evaluated in the Appendix O environment.
  - Freezing drizzle <40
  - Freezing drizzle >40
  - Freezing rain <40
  - Freezing rain >40
- Performance evaluated in “High” and “Max” modes of operation.
  - Critical temperatures found for anti-ice operation for each mode in each environment
  - Performance evaluated in “Max” mode at coldest temperatures when anti-ice protection could not be achieved

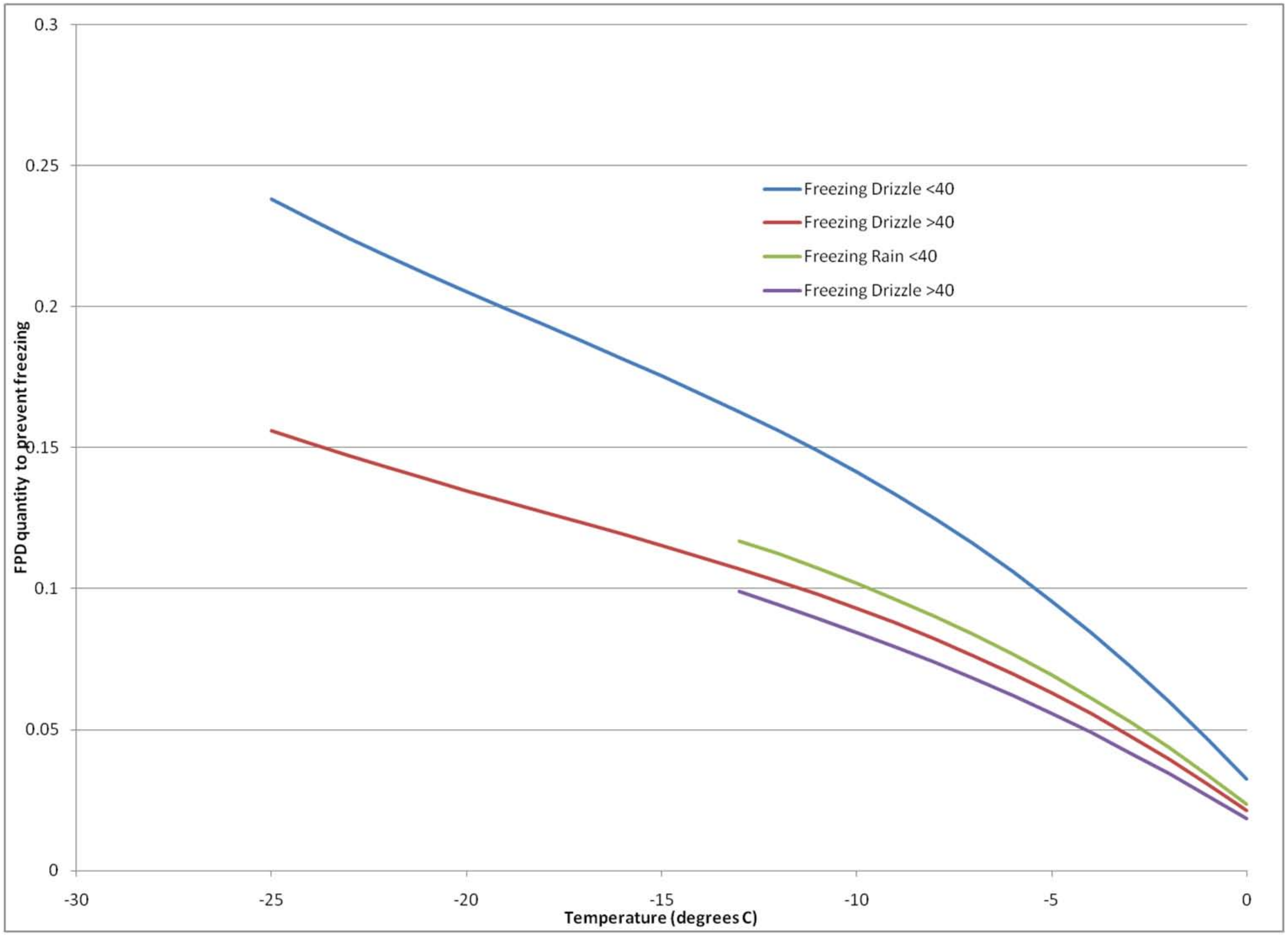
Performance in Appendix O



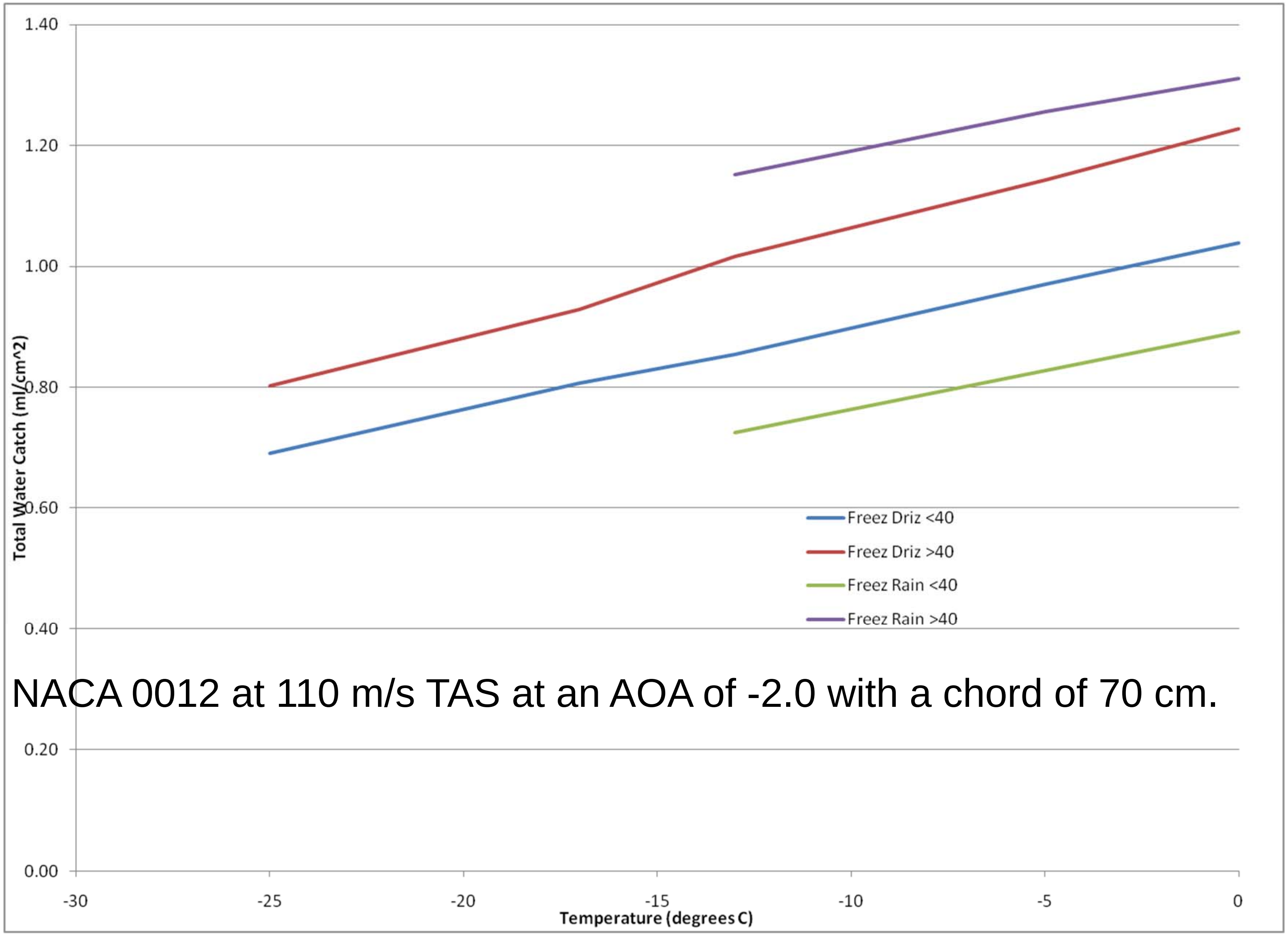
Appendix O LWC Chart

Performance in Appendix O

FDP Liquid required to prevent freezing.
(Unity catch efficiency)



Performance in Appendix O

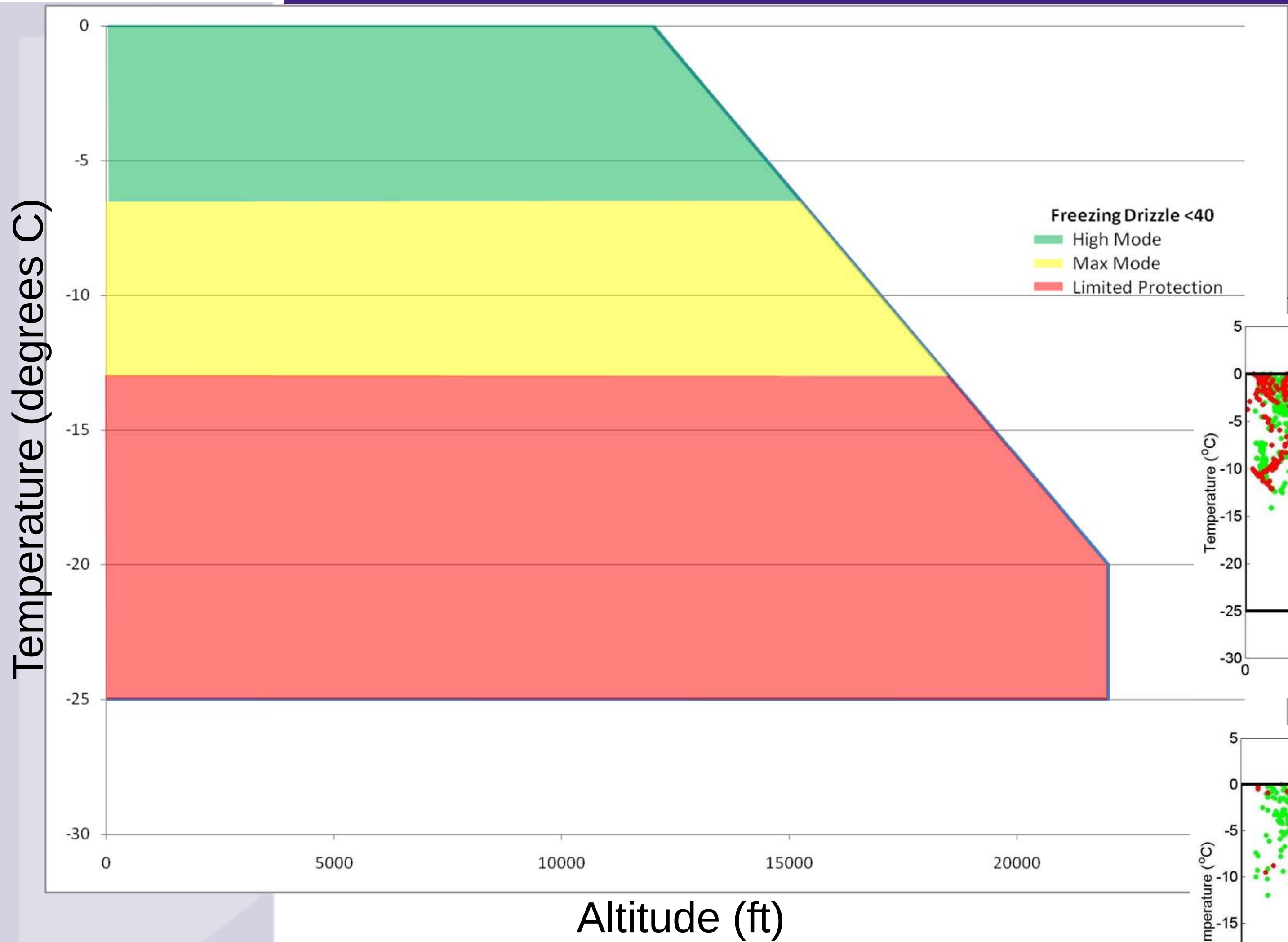


Total Water Catch Example

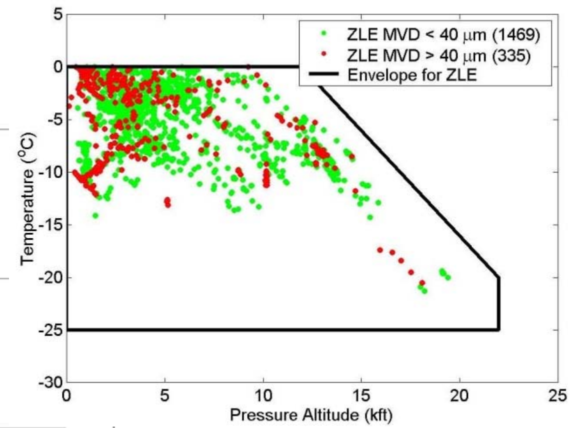
Performance in Appendix O

				FD GT 40	FD LT 40	FR GT 40	FR LT 40
Wing	Tip	Cruise	High Crit	-7	-9	-6	-9
			Max Crit	-12	-18.5	-10	-13
		Climb	High Crit	-4	-6.5	-5	-7.5
			Max Crit	-8.5	-14.5	-9	-13
	Root	Cruise	High Crit	-6	-8	-5.5	-7.5
			Max Crit	-10	-15.5	-8.5	-13
		Climb	High Crit	-4	-6.5	-4	-6.5
			Max Crit	-7	-13	-7.5	-13
Tail	Tip	Cruise	High Crit	-9.5	-11	-8	-12.5
			Max Crit	-21.5	-25	-13	-13
		Climb	High Crit	-8	-10	-8.5	-13
			Max Crit	-20	-25	-13	N/A
	Root	Cruise	High Crit	-8	-9.5	-7	-10
			Max Crit	-15	-22.5	-12	-13
		Climb	High Crit	-7	-9.5	-7	-12
			Max Crit	-15.5	-25	-13	-13

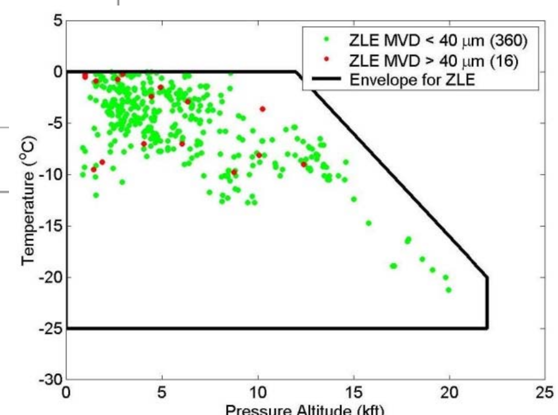
Performance in Appendix O



3 - km Data

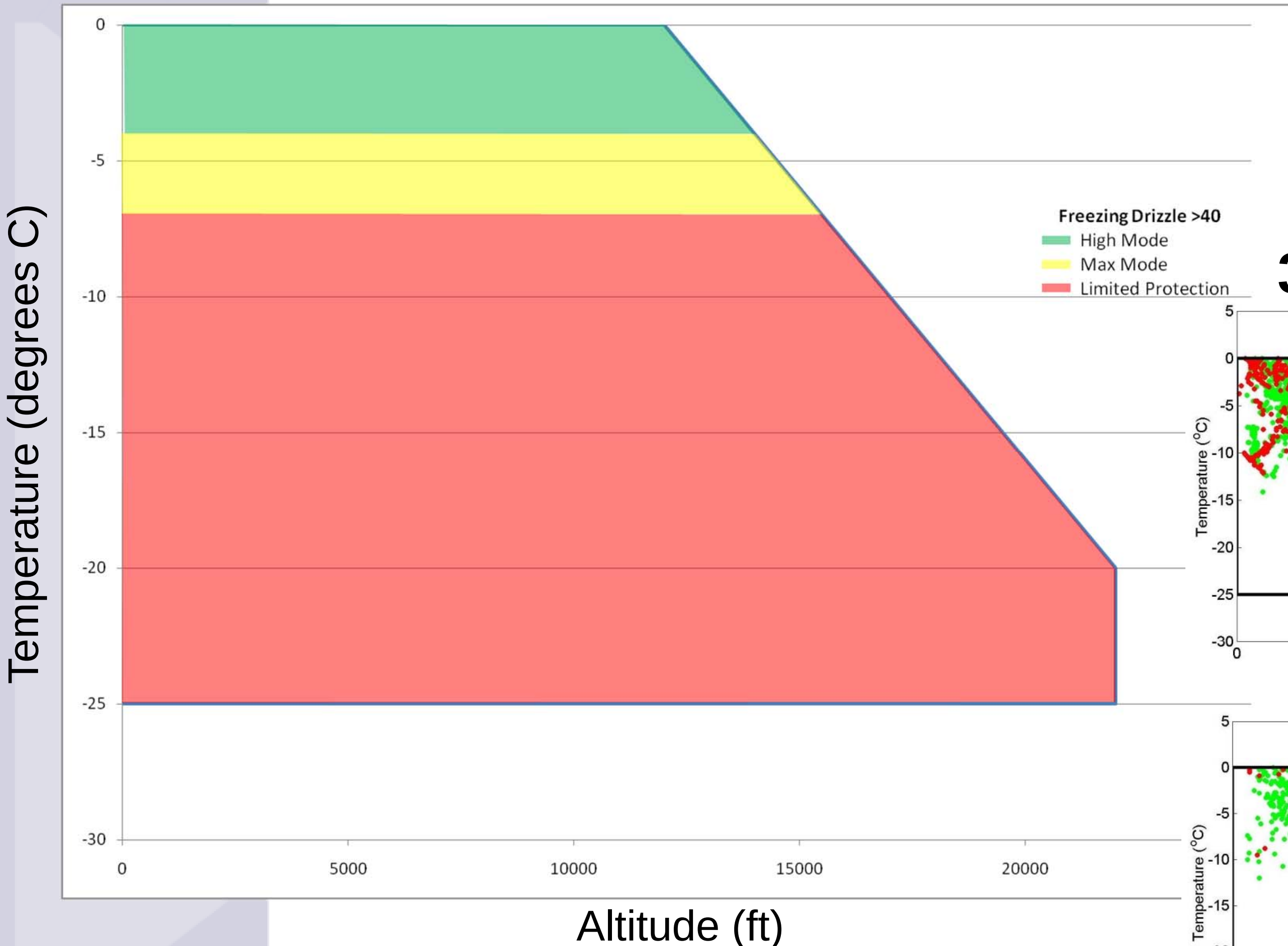


Freezing Drizzle <40



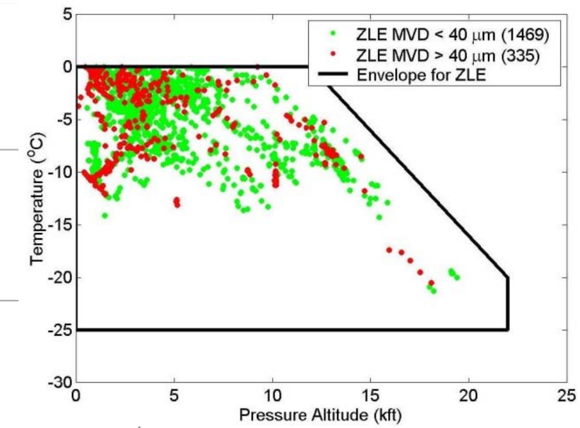
30 – km Data

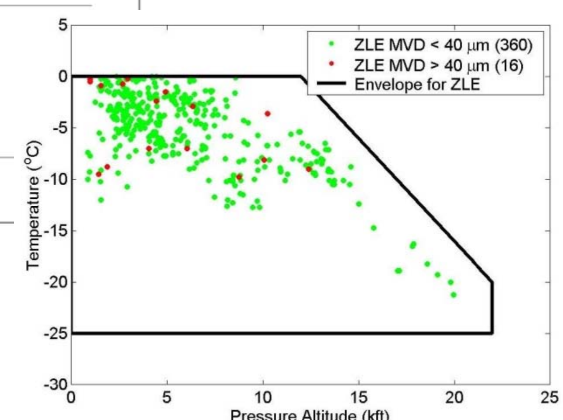
Performance in Appendix O



Freezing Drizzle >40

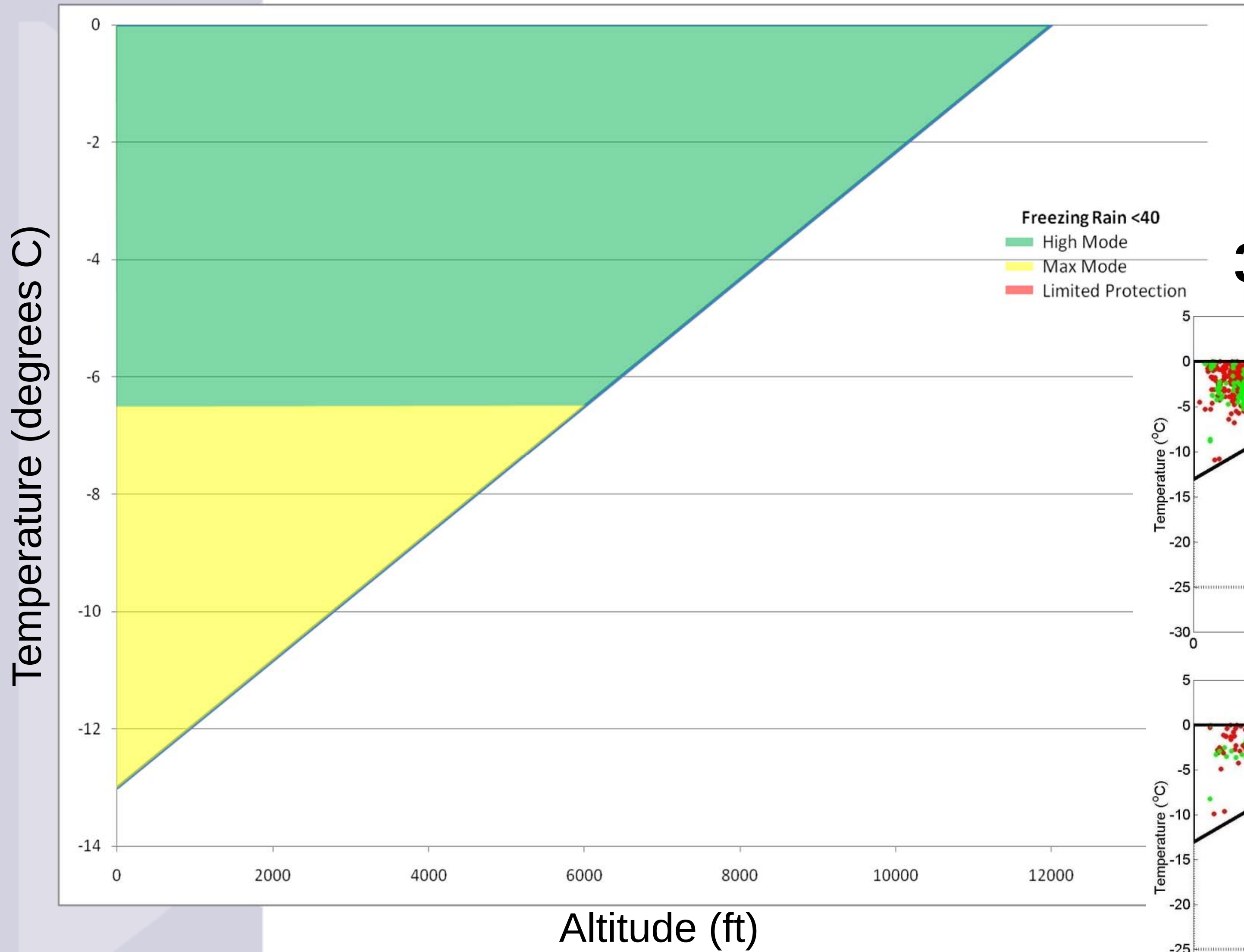
3 - km Data





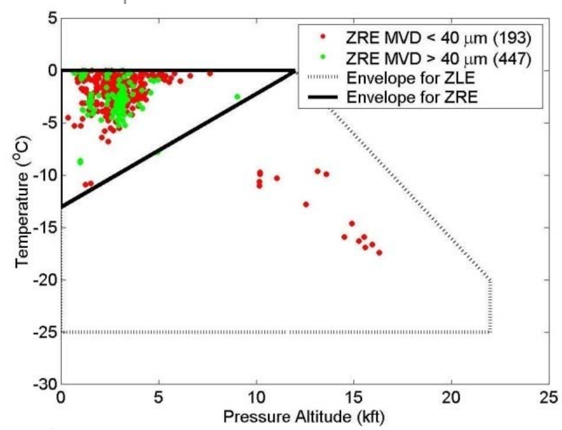
30 – km Data

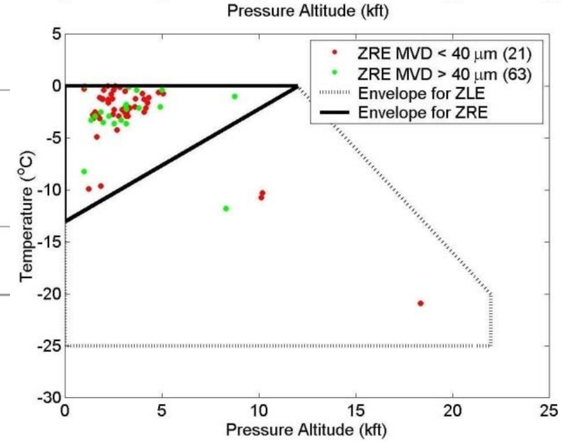
Performance in Appendix O



Freezing Rain <40

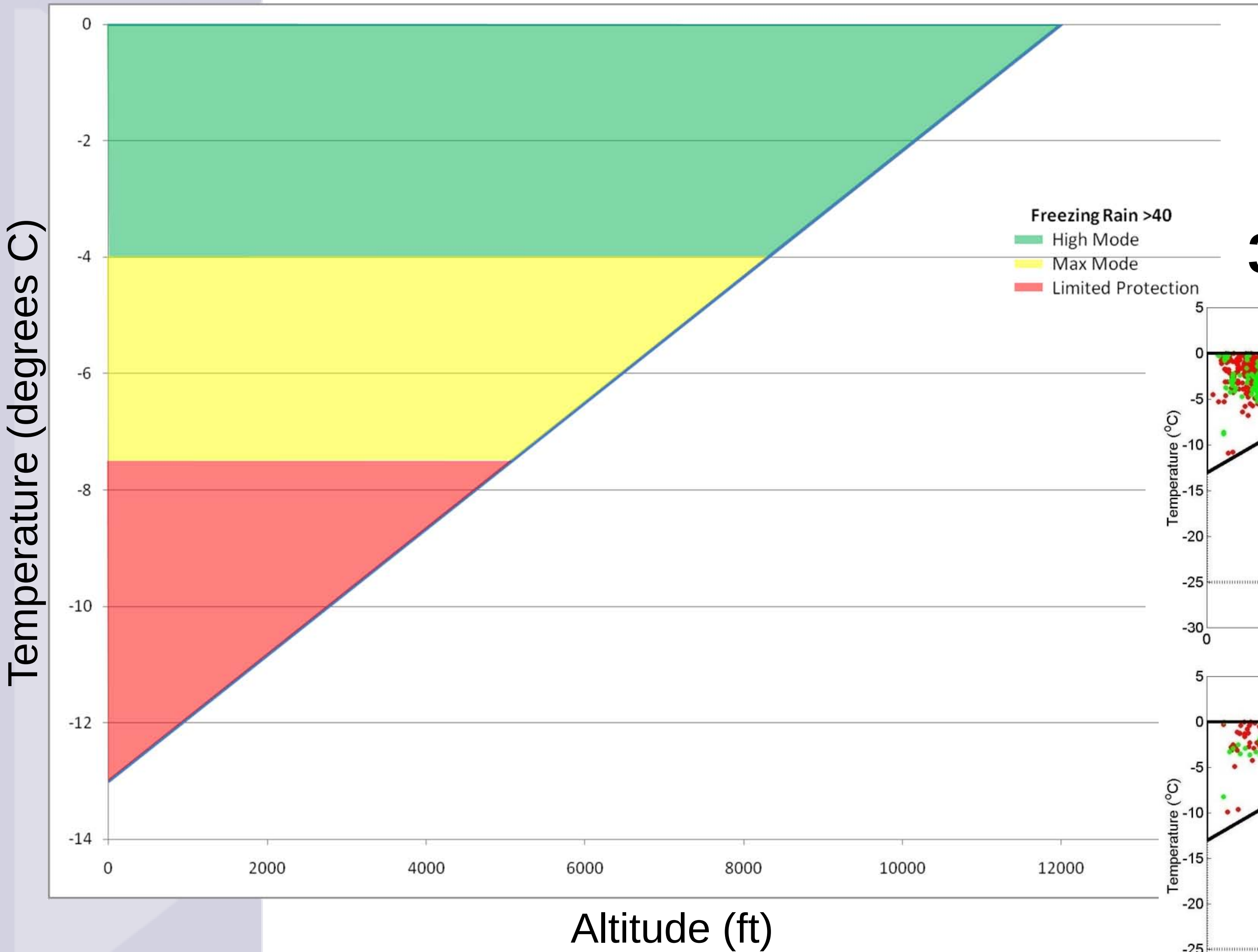
3 - km Data





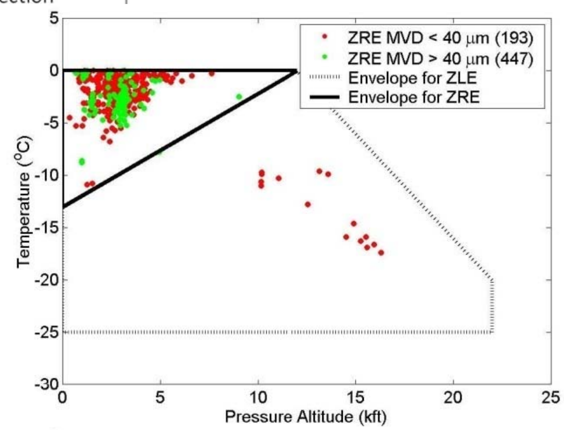
30 – km Data

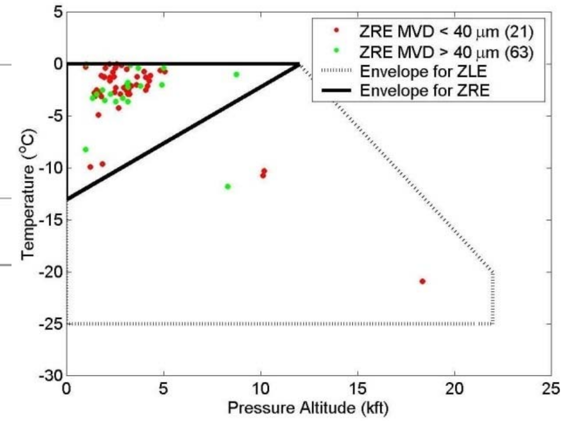
Performance in Appendix O



Freezing Rain >40

3 - km Data





30 – km Data

Performance in Appendix O

- General observations on defining protection envelope
  - Root of the panel was more critical than the tip.
  - Wing airfoil was more critical than tail.
  - Climb more critical than cruise

Certification Considerations

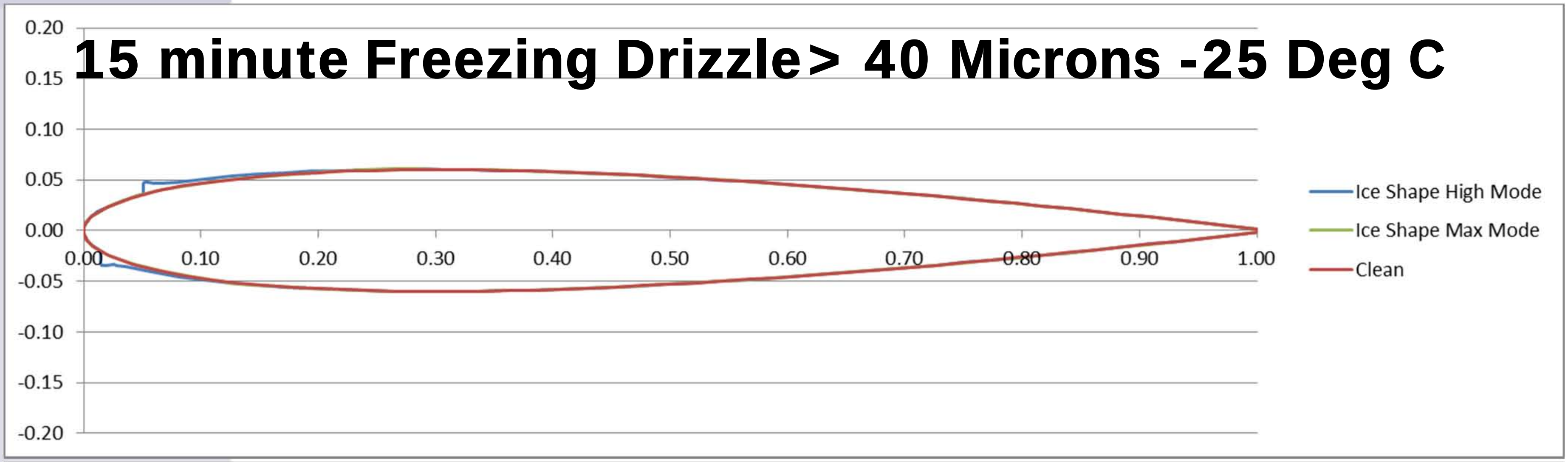
- **Possible operational procedures within Appendix O environment**
  - **Detect and exit**
  - **Certify for continued operation over a portion of the environment and detect and exit over remaining portion**
  - **Certify for continued operation within entire envelope**
- **System design considerations**
  - **Increase panel size to fully protect in Appendix O**
  - **Tank size for various types of operation**
    - **Increasing panel size increases overall flow rate and therefore, size of tank needed.**
    - **Operating in Appendix O environment requires higher flow rate.**

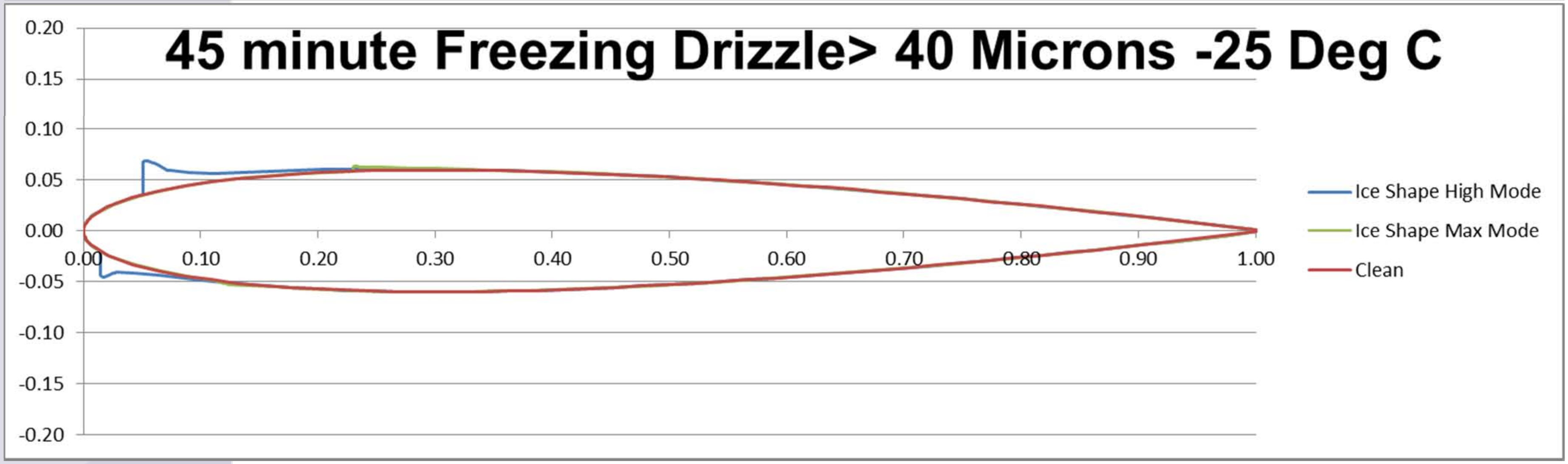
Certification Considerations

- **Performed analysis to determine panel size increase to provide anti-ice solution in appendix O using Max mode**
  - **Freezing drizzle greater than 40 at -25C is critical case**
  - **Results indicate overall wing design flow rate increases 3.3x+ from the Appendix C design**
  - **Results indicate overall tail design flow rate increases 2.3x+ from the Appendix C design**

	Tip sle App. C (cm)	Tip sle App. O (cm)	Tip % Change	Root sle App. C (cm)	Root sle App. O (cm)	Root % Change
Wing	6.271	9.822	56.6%	6.544	11.844	81.0%
Tail	3.304	3.540	7.1%	3.733	4.832	29.4%

Possible Certification Ice Shapes

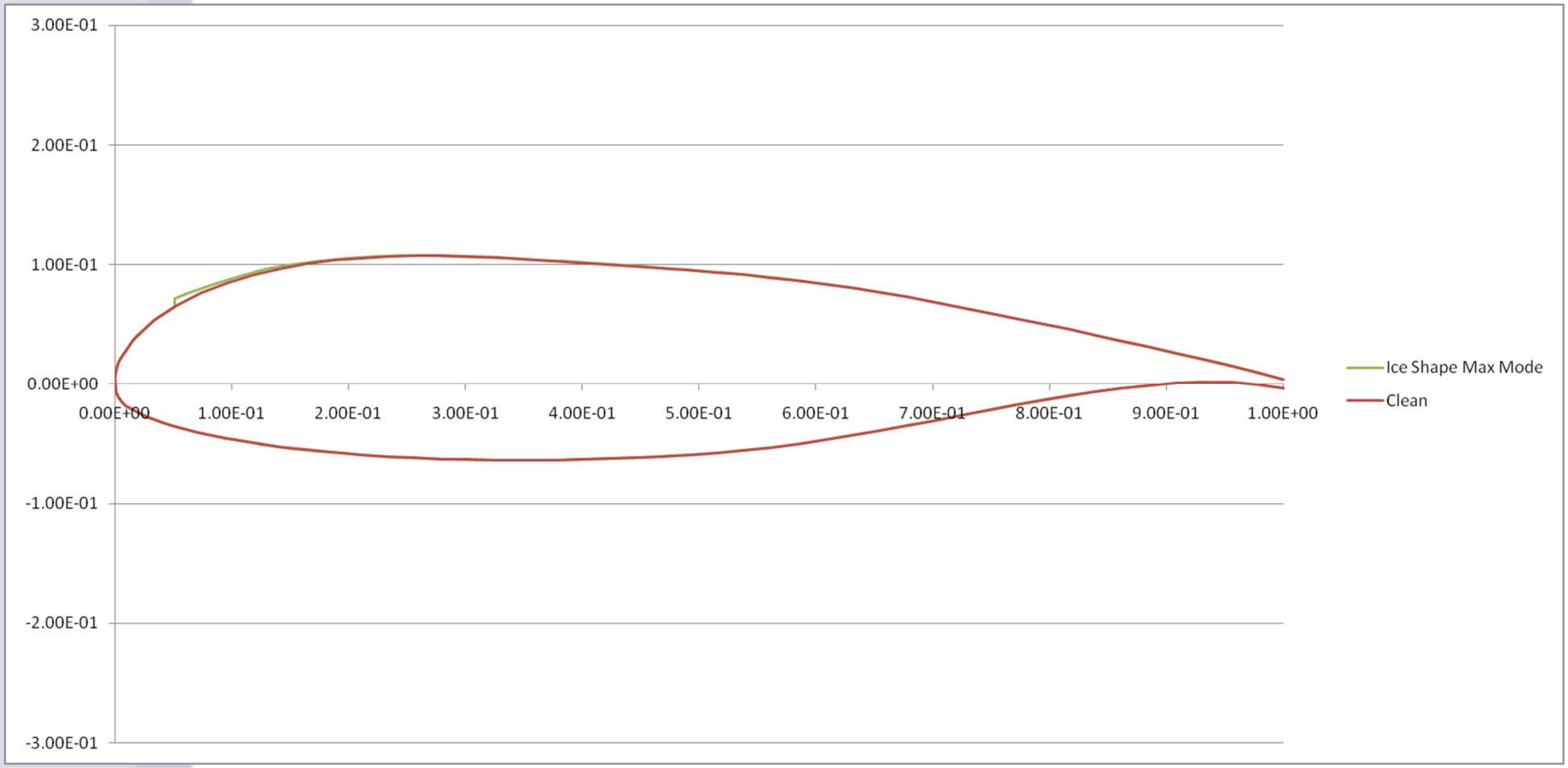




NACA 0012 at 110 m/s TAS at an AOA of -2.0 with a chord of 70 cm.

Possible Certification Ice Shapes

15 minute Freezing Drizzle> 40 Microns -25 Deg C

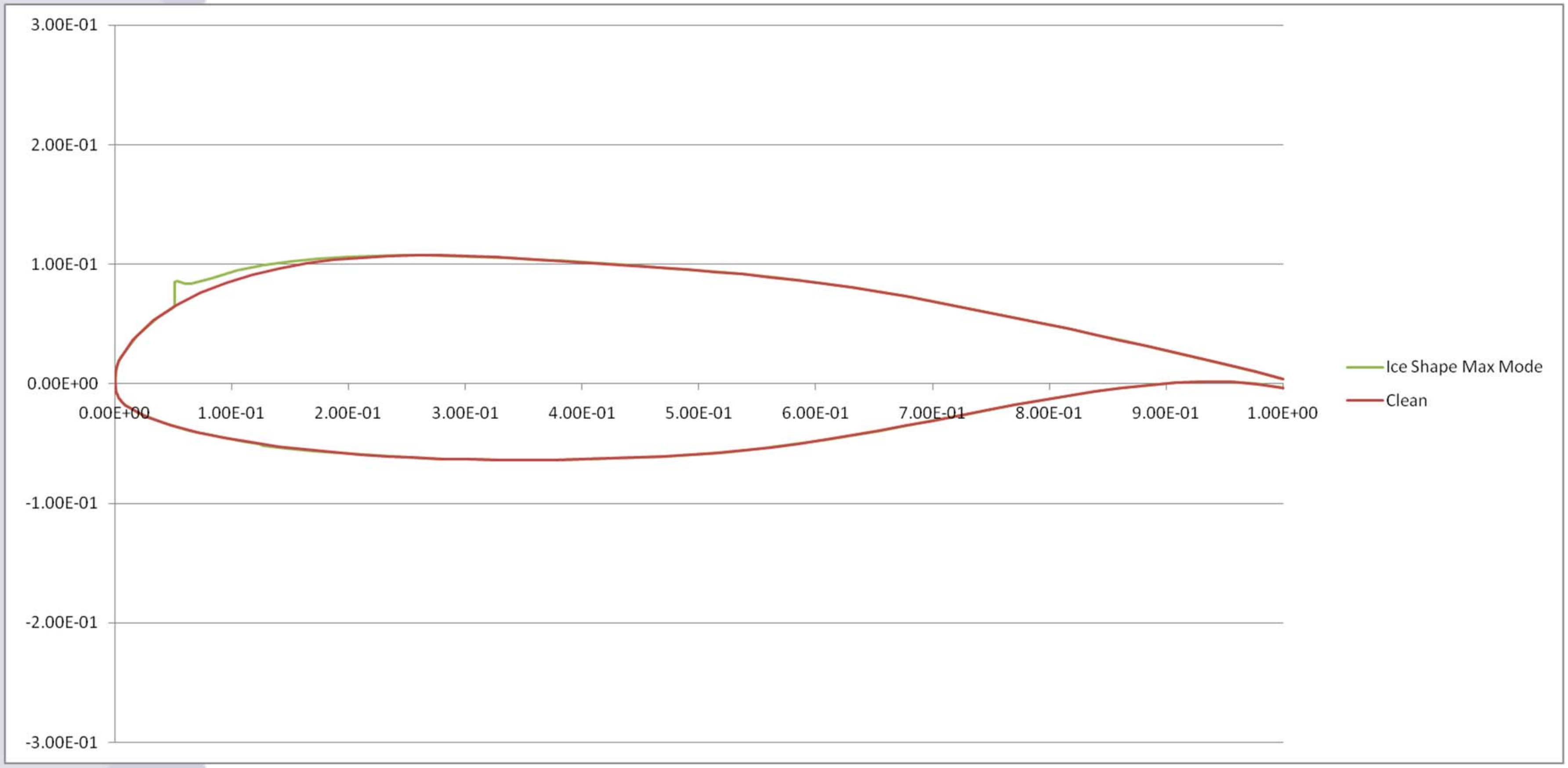


Wing at 110 m/s TAS at an AOA of -2.2 with a chord of 125 cm.

Max thickness of ~0.25"

Possible Certification Ice Shapes

45 minute Freezing Drizzle> 40 Microns -25 Deg C

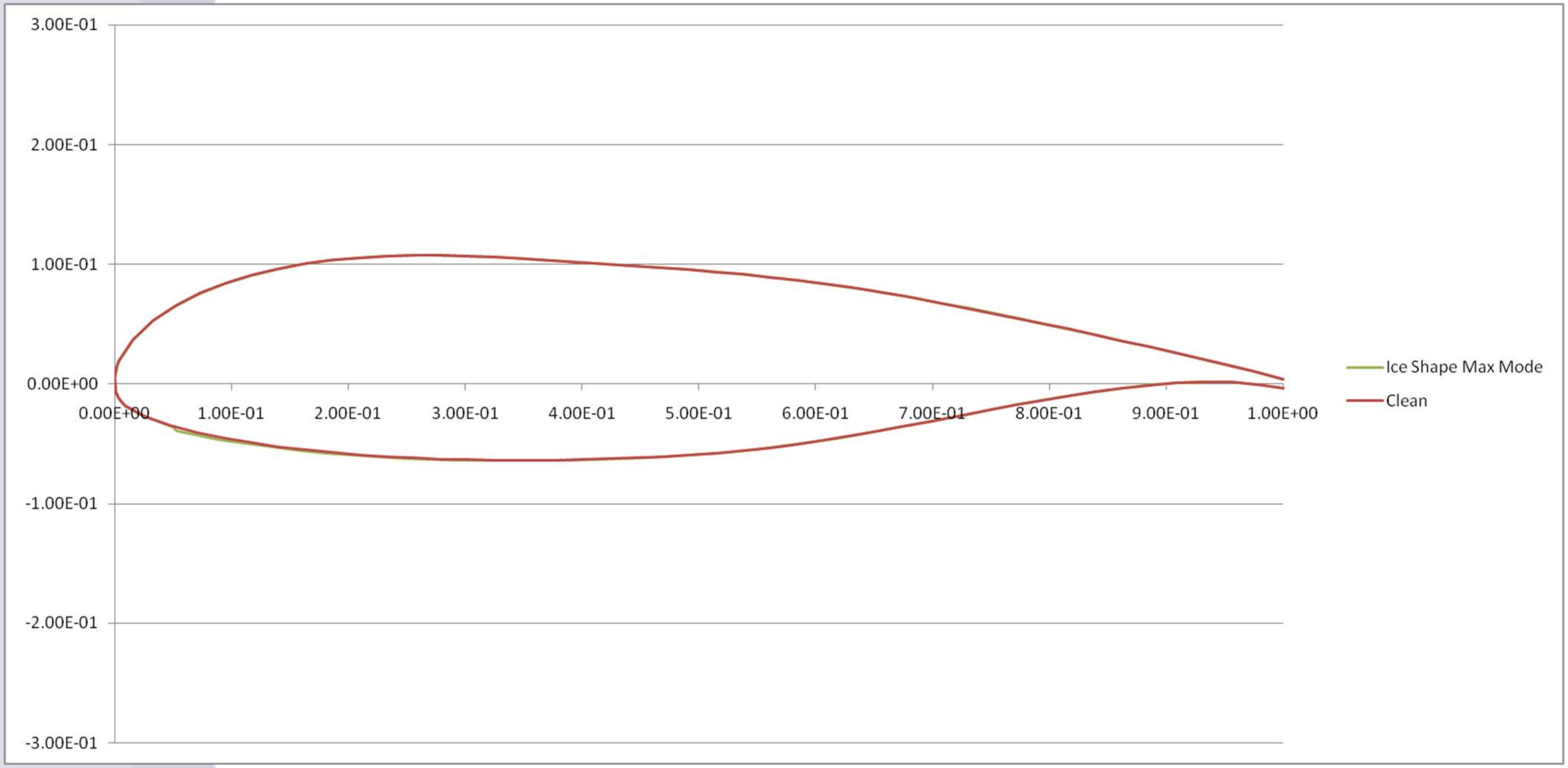


Wing at 110 m/s TAS at an AOA of -2.2 with a chord of 125 cm.

Max thickness of ~0.9"

Possible Certification Ice Shapes

15 minute Freezing Drizzle> 40 Microns -25 Deg C

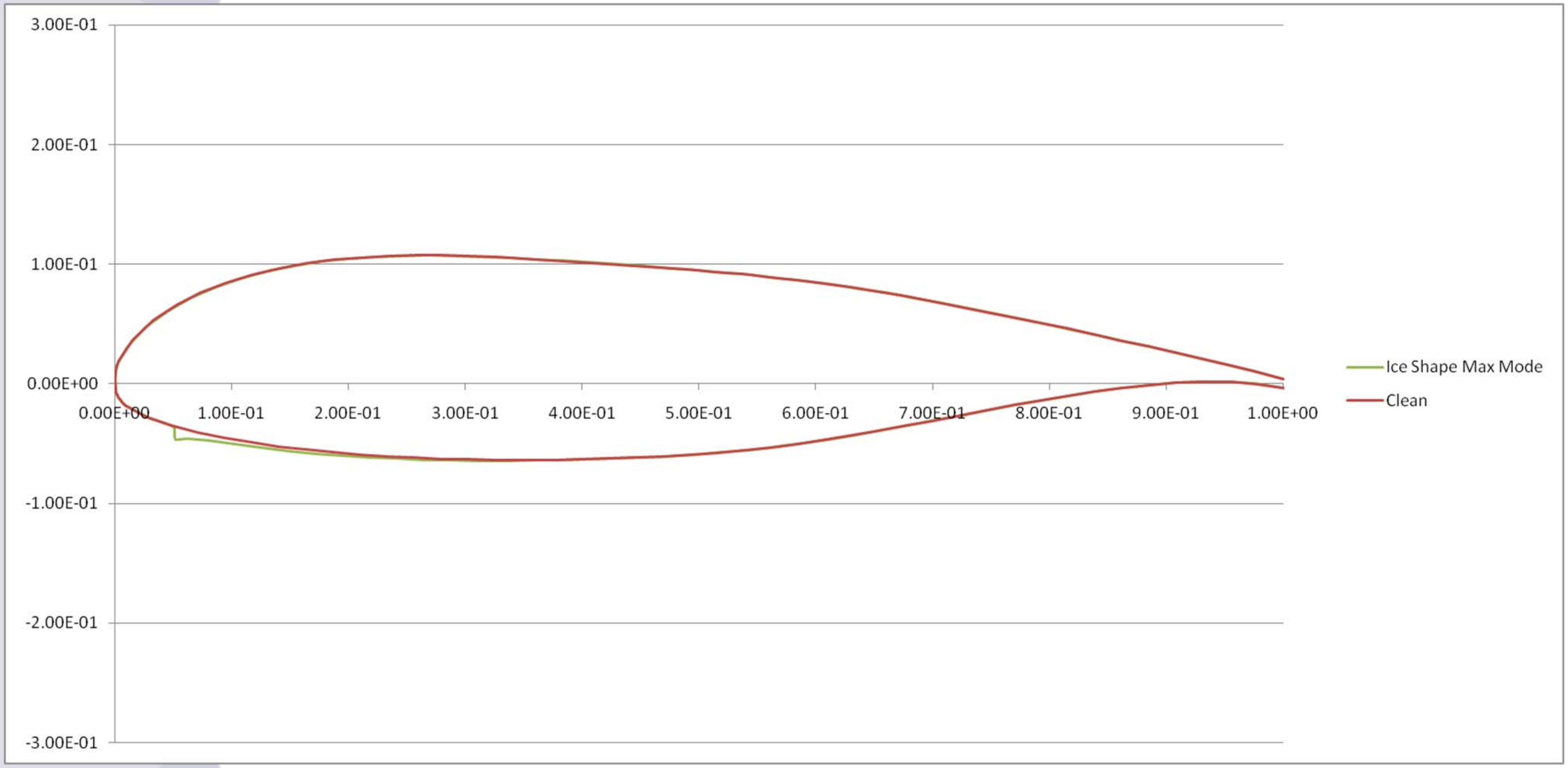


Wing at 75 m/s TAS at an AOA of 2.2 with a chord of 125 cm.

Max thickness of ~0.13"

Possible Certification Ice Shapes

45 minute Freezing Drizzle> 40 Microns -25 Deg C



Wing at 75 m/s TAS at an AOA of 2.2 with a chord of 125 cm.

Max thickness of ~0.5"

Icing Wind Tunnel Tests

- During November of 2010 some preliminary IWT tests were performed by CAV at the Cox LeClerc IWT facility.
- Testing was done on a model representative of the generic airfoil the analysis was performed on.
- Tunnel only capable of producing a cloud of limited size in the middle of tunnel
- Tunnel was limited to freezing drizzle > 40 microns.
  - Previously measured tunnel conditions were 98 microns with an LWC of 0.793 g/m^3 @ 170 mph.
  - 7 bin, Langmuir-D distribution used to simulate tunnel spray for analysis purposes

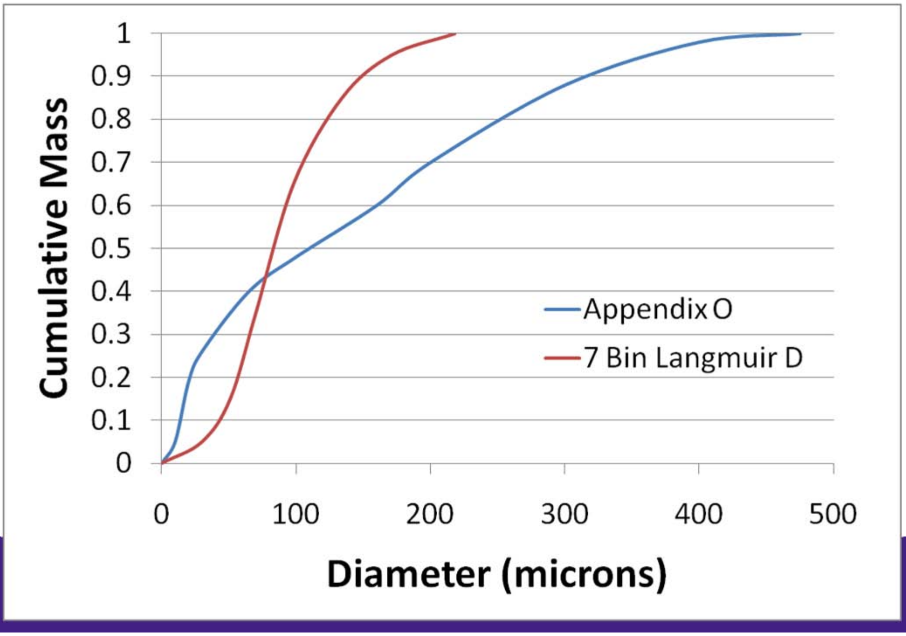
Icing Wind Tunnel Tests

- Analytical comparisons were made between a Langmuir-D distribution and the appendix O defined distribution
- Tunnel calibration was done at 170 mph, while analysis was done at 246 mph (110 m/s).
- Tunnel speed was scaled for dynamic pressure to 201 mph.
- Therefore, for analytical purposes, LWC was assumed to change linearly with speed
  - Tunnel LWC @ 201 mph assumed to be 0.671 g/m^3 with a droplet size of 98 microns
  - Desired LWC ranged from 0.19 to 0.262 g/m^3
  - TKS fluid flow for each condition is scaled to match ratio of expected tunnel LWC to desired LWC

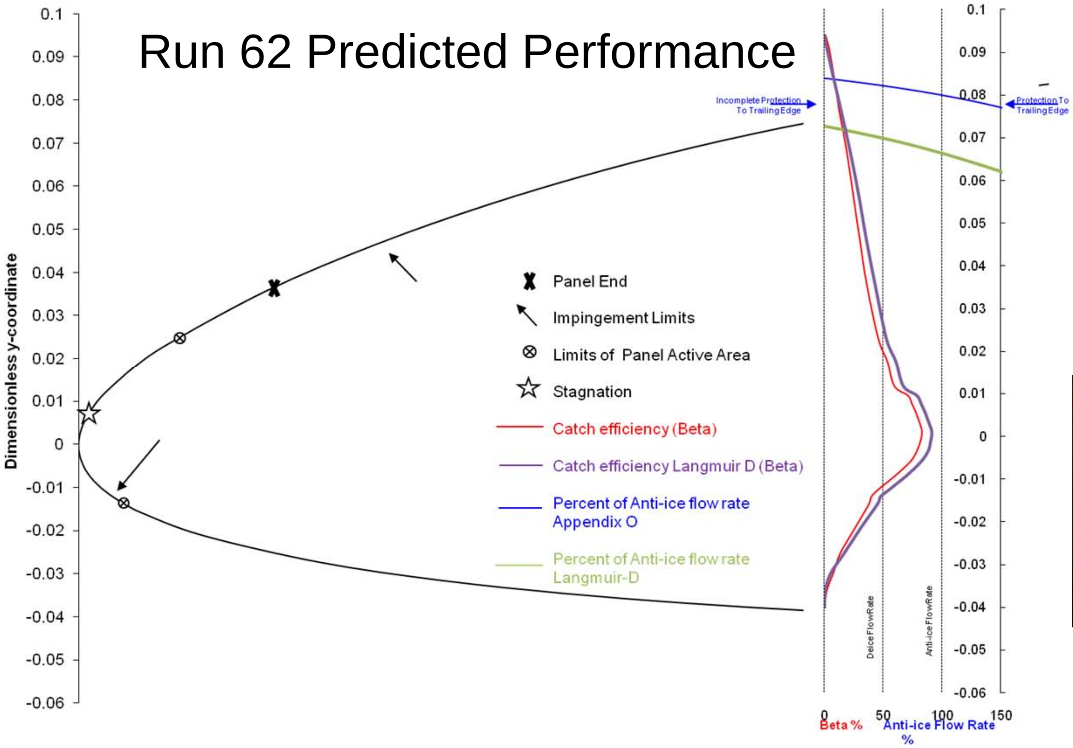
Icing Wind Tunnel Tests

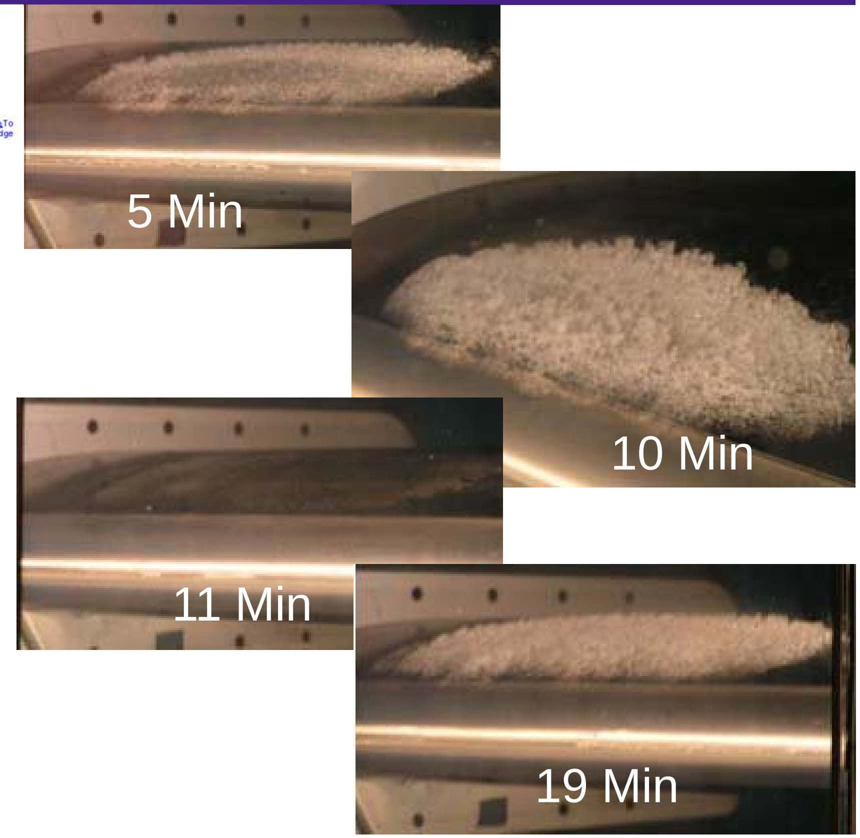
Run #	System Setting	Temperature (°C)	Desired LWC (g/m^3)	Estimated Tunnel LWC (g/m^3)	Actual Intercept Time (min)	Scaled Intercept Time (min)	Description of Expected Performance
62	High	-7.0	0.262	0.671	Approx 19	Approx 49	Anti-ice on lower surface, small area of de-ice performance on upper surface
63	Max	-7.0	0.262	0.671	Approx 9	Approx 23	Anti-ice on entire airfoil
64	Max	-12.0	0.242	0.671	Approx 12.5	Approx 35	Anti-ice on lower surface, small area of de-ice performance on upper surface
65	Max	-25.0	0.190	0.671	Approx 15	Approx 53	Anti-ice on lower surface, limited protection on upper surface

Comparison of a 7 Bin Langmuir-D Distribution for 98 Microns and Defined Appendix O Distribution for Freezing Drizzle > 40



Icing Wind Tunnel Tests



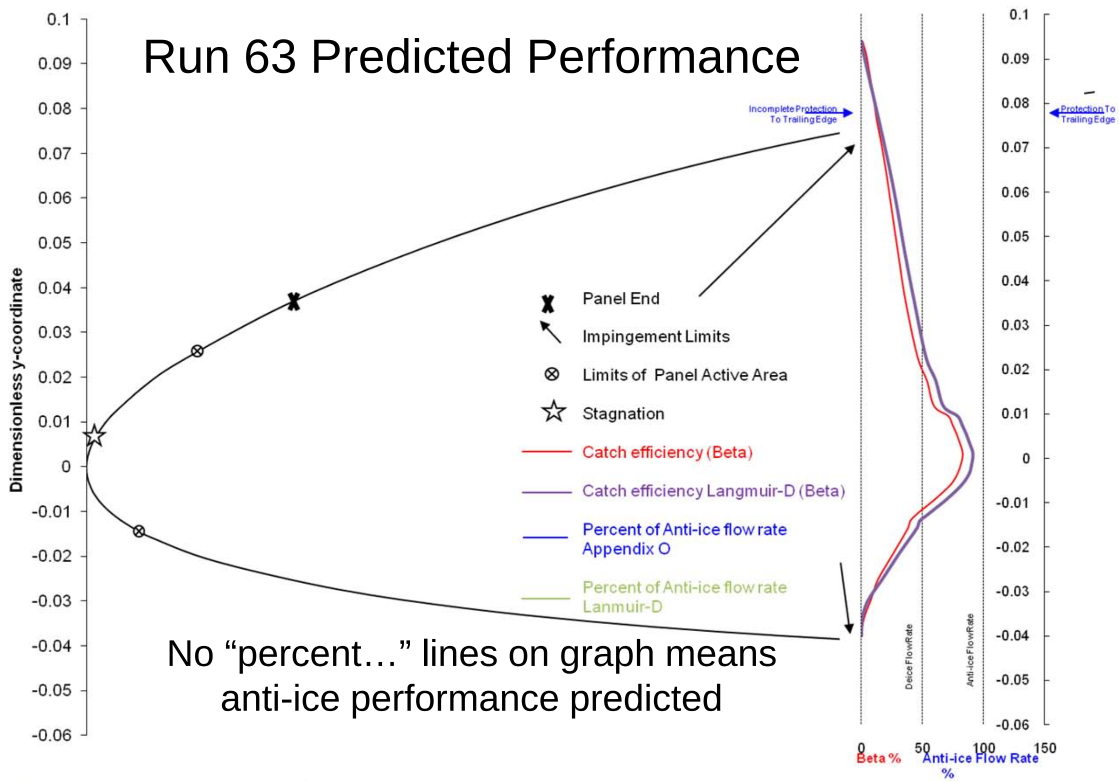


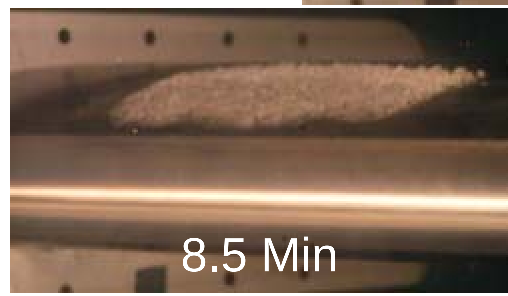
- **Full shed 11 minutes into run**
- **Ice extends to ~20% chord (ice was ~7” wide along chord)**
- **No ice observed on lower surface**
- **More ice seen than expected from analysis**
- **Run stopped at 19 min to try and contain “largest” ice shape prior to 2nd shed cycle for measurement**

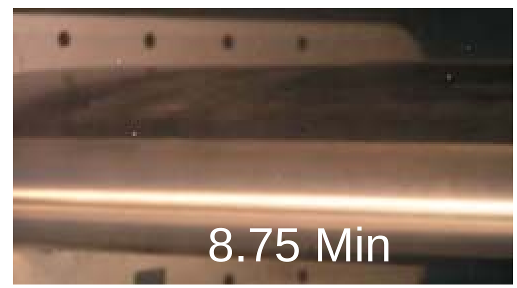
Estimated x/c	Ice Thickness (in)
0.035 (End of panel)	0.06
0.077	0.222
0.12	0.325
0.16	0.328
0.20	0.371

Ice Thickness Measured at 19 Min

Icing Wind Tunnel Tests

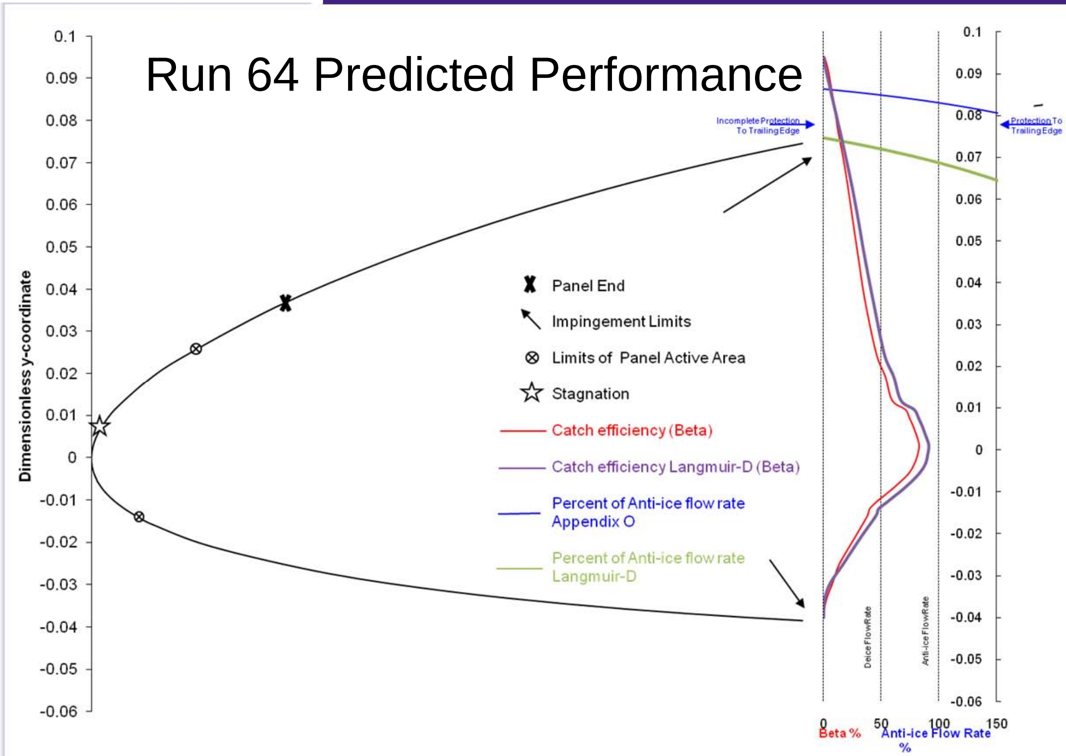


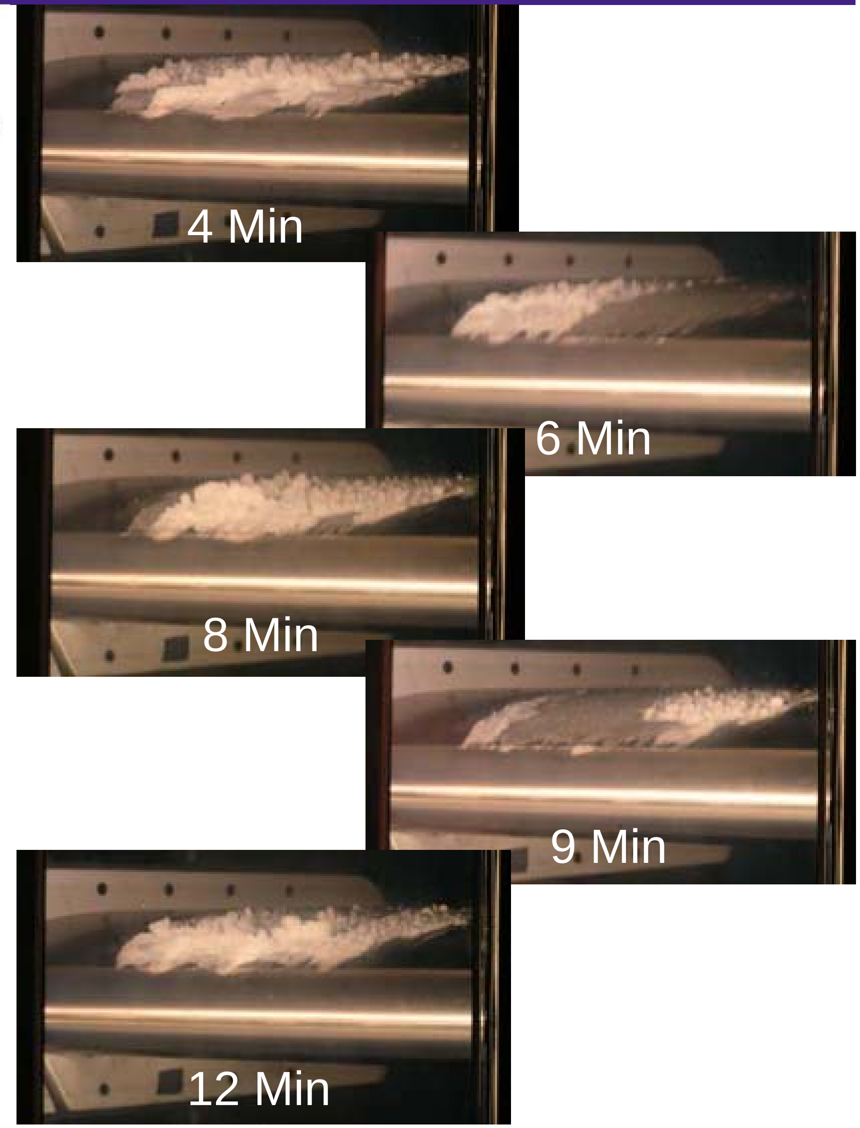




- **Fully shed at 3.75 and 8.75 min into run**
- **Ice shape estimated as no worse than standard roughness used for delayed start**
- **No ice observed on lower surface**
- **Anti-ice performance expected, but de-ice observed**
- **Run stopped after 2 shed cycles as results were viewed as repeatable**

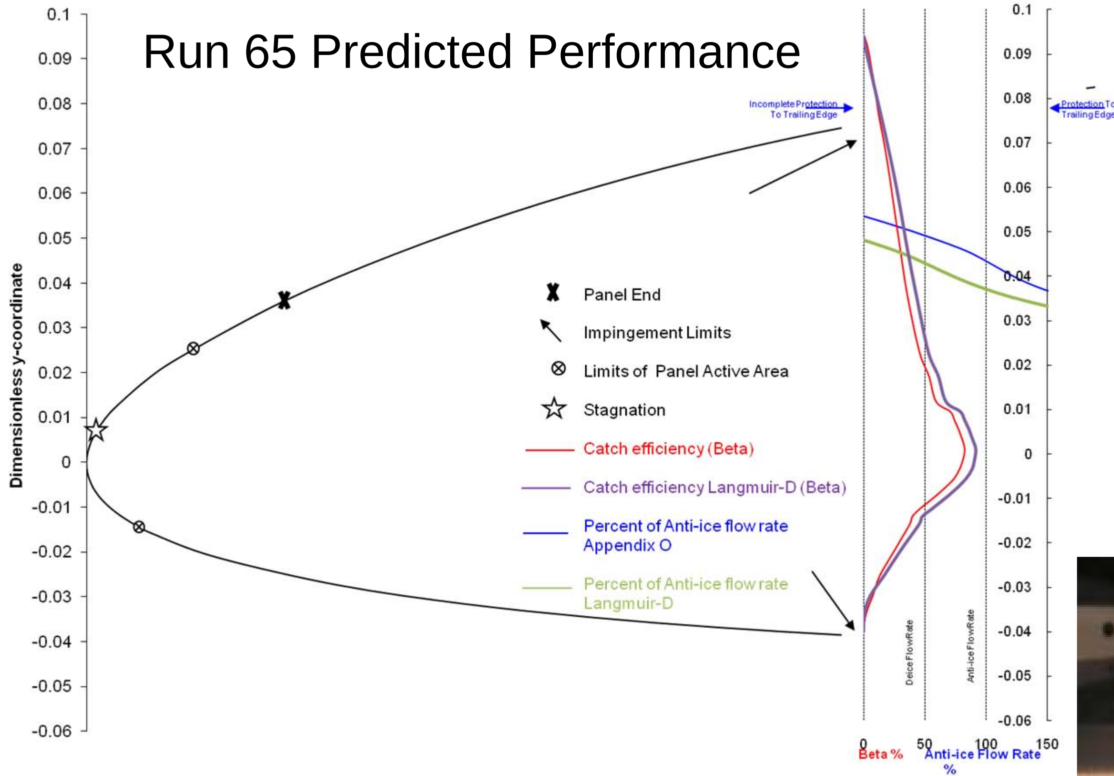
Icing Wind Tunnel Tests

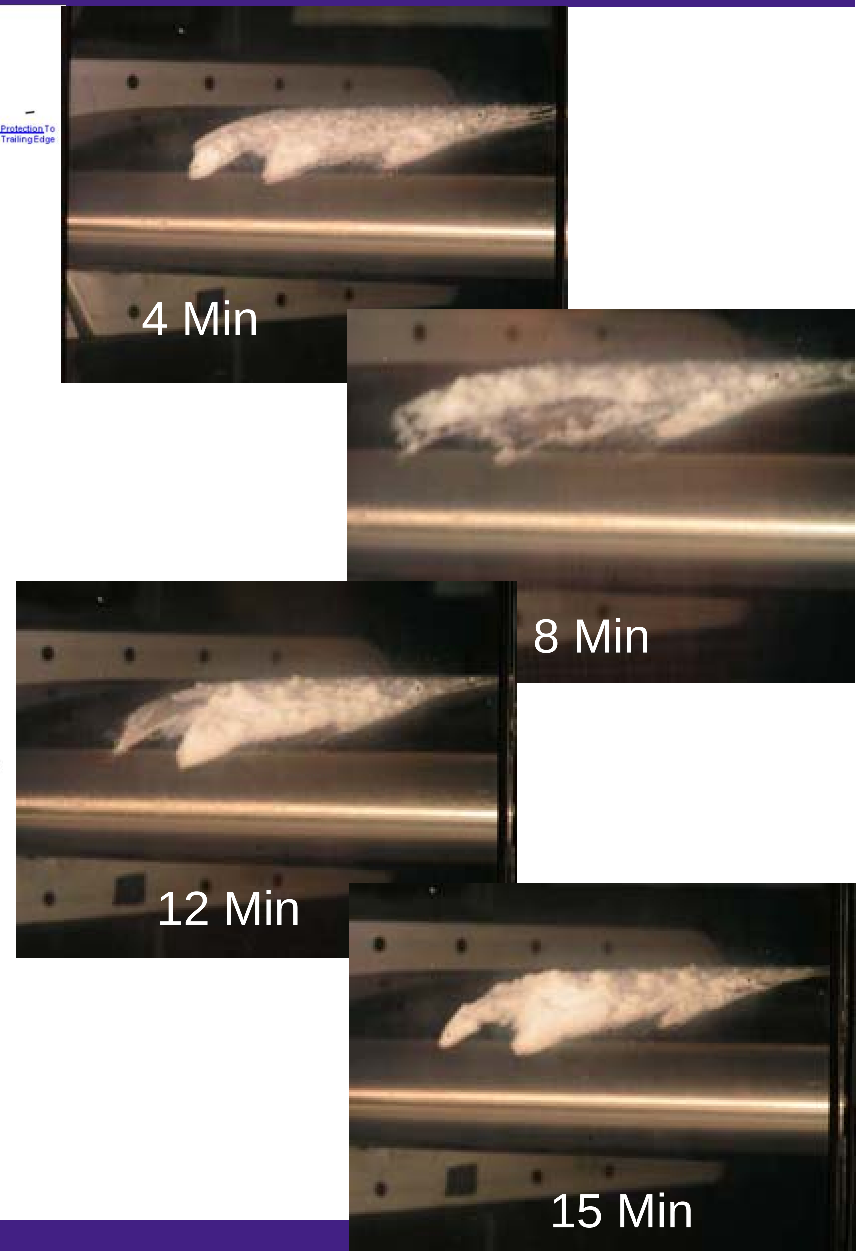




- **Partial sheds constantly throughout run**
- **Ice extends to ~40% chord**
- **Thickest point of shape estimated at ~0.75in**
- **No ice observed on lower surface**
- **More ice seen than expected from analysis**
- **Run stopped at 12 min to try and contain "largest" ice shape for measurement, but ice detached from model during shutdown**

Icing Wind Tunnel Tests





- **Partial sheds at 8 and 12 minutes into run**
- **Ice extends to ~40% chord**
- **Thickest point of shape ~1in**
- **No ice observed on lower surface**
- **Upon shutdown of tunnel ice was observed as "slushy" rather than solid ice**

Icing Wind Tunnel Tests

- System was demonstrated to have the ability to de-ice during less severe encounters and had limited protection at critical condition (run 65)
- Verbally informed by tunnel personal that actual provided LWC could be as much as 1.5 times the expected LWC
- Effects of 2.5 – 3 x scaling on the ability to accurately predict performance is unknown
- The ice shape developed during run 65 was similar to predicted shape in size and location (see slide 28)
  - Extents and maximum thickness similar
  - Front of actual shapes were more sloped than predicted shapes
- Further icing tunnel testing in better defined conditions closer to defined appendix O environment is highly desired to study the performance of TKS and accuracy of analytical tools in the appendix O environment

Conclusions and Future Work

- FDP system provides anti-ice protection over portions of the Appendix O envelope with current design process.
- Certification for either detect and exit or continuous operation will likely require some type of ice shape or changes to panel design.
- As capabilities of icing tunnels expand, continued work to investigate extents of protection is desired to verify analytical results.