NASA Glenn Icing Research Tunnel Upgrade and Cloud Calibration

In 2011, NASA Glenn's Icing Research Tunnel underwent a major modification to it's refrigeration plant and heat exchanger. This paper presents the results of the subsequent full cloud calibration. Details of the calibration procedure and results are presented herein. The steps include developing a nozzle transfer map, establishing a uniform cloud, conducting a drop sizing calibration and finally a liquid water content calibration. The goal of the calibration is to develop a uniform cloud, and to build a transfer map from the inputs of air speed, spray bar atomizing air pressure and water pressure to the output of median volumetric droplet diameter and liquid water content.

IRT 2011-12 Cooling System Upgrade

NASA Glenn Icing Research Tunnel

Upgrade and Cloud Calibration

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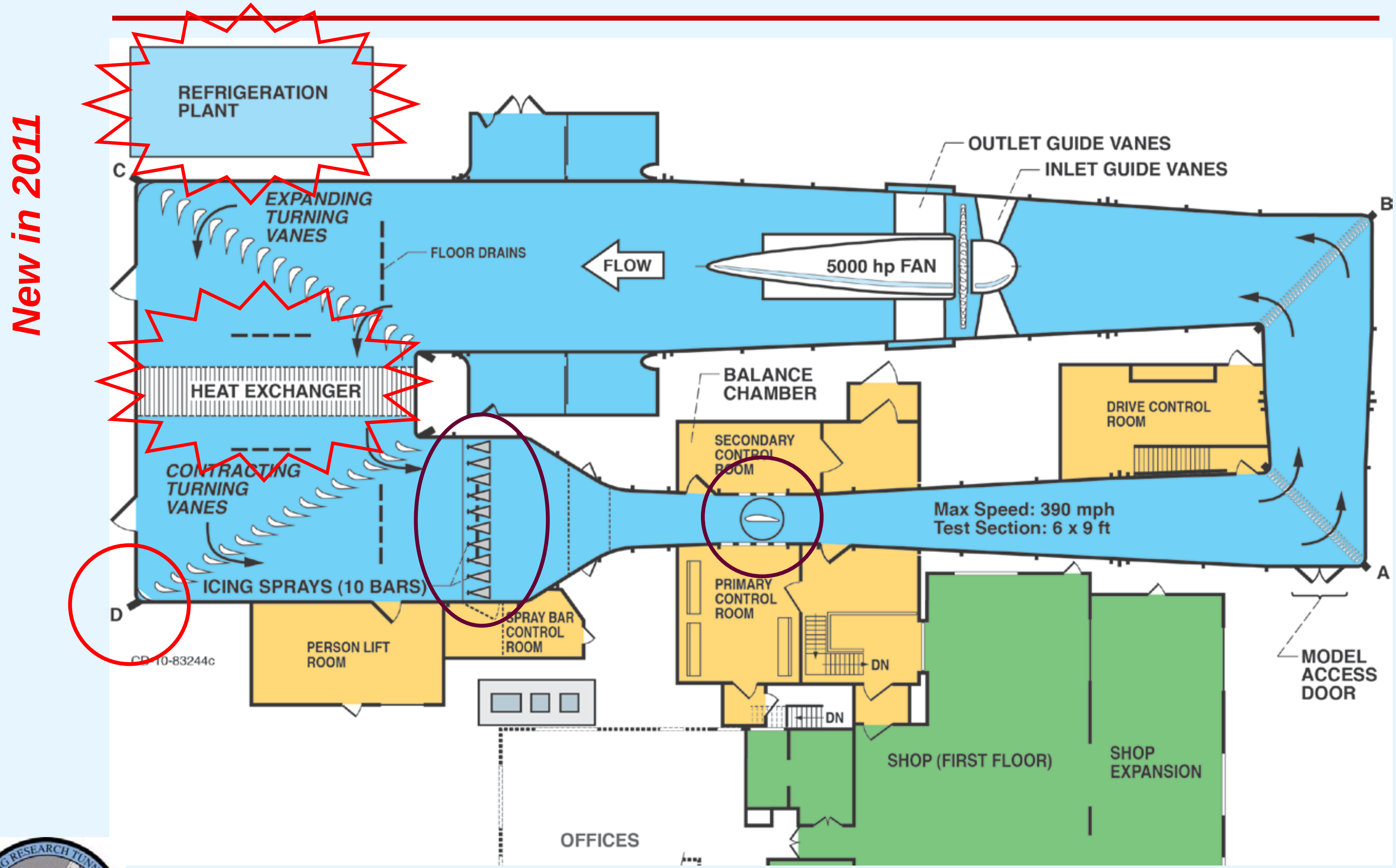
Robert F. Ide / Sierra Lobo, Inc.
Laura E. Steen / Sierra Lobo, Inc.

Session Summary

Time	Topic	Presenter
0800 – 0900	**IRT Upgrade and Cloud Cal**	**Van Zante / NASA-SLI**
0900 – 0930	IRT Test Section Aero-Thermal Cal	Pastor-Barsi / NASA-SLI
0930 – 1000	IRT Plenum Aero-Thermal Cal	Steen / NASA-SLI
1000 – 1030	VIRT: Air Flow and Liquid Water Concentration Simulations	Clark / UVa
1030 – 1100	VIRT: Drop Concentration and Flux on Aerodynamic Surfaces	Triphahn / UIUC
1100 – 1130	3D Laser Scanner in IRT	Lee / NASA-VGI

2012 Icing Research Tunnel



Test Facilities Operation, Maintenance & Engineering

Outline

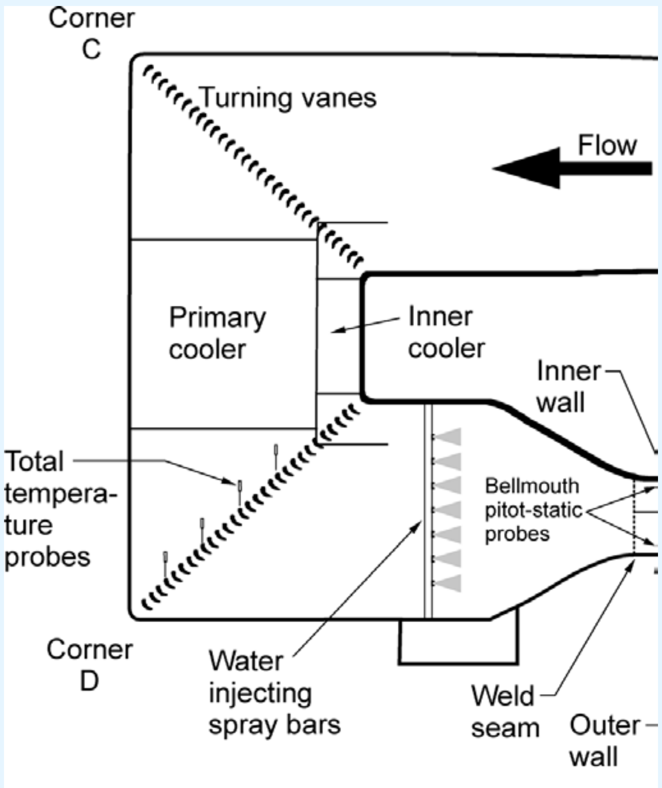
1. 2011 Refrigeration Plant and Heat Exchanger Upgrade

2. Cloud Characterization & Calibration

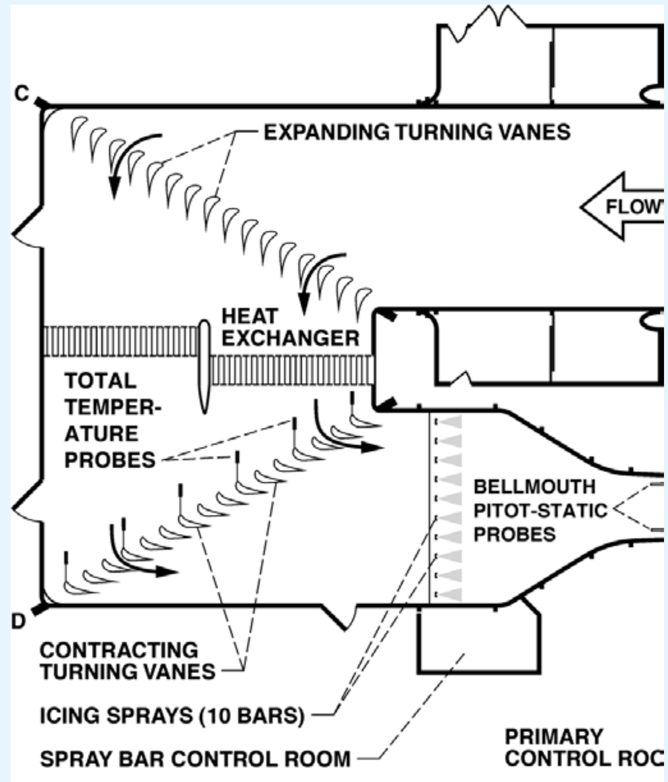
2011 Refrigeration Plant and Heat Exchanger Upgrade

Test Facilities Operation, Maintenance & Engineering

Previous two IRT HX Configurations



1997 Configuration
("W" heat exchanger)



2000 Configuration
(flat heat exchanger)

Test Facilities Operation, Maintenance & Engineering

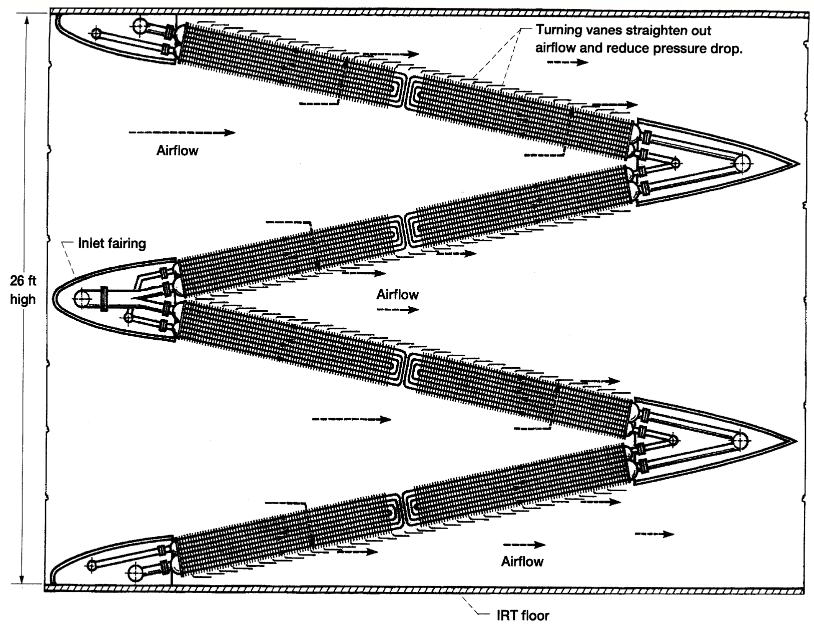
Original 1940's Refrigeration Plant & Heat Exchanger

Refrigeration Plant

<u>Temperatures down to -45F</u>

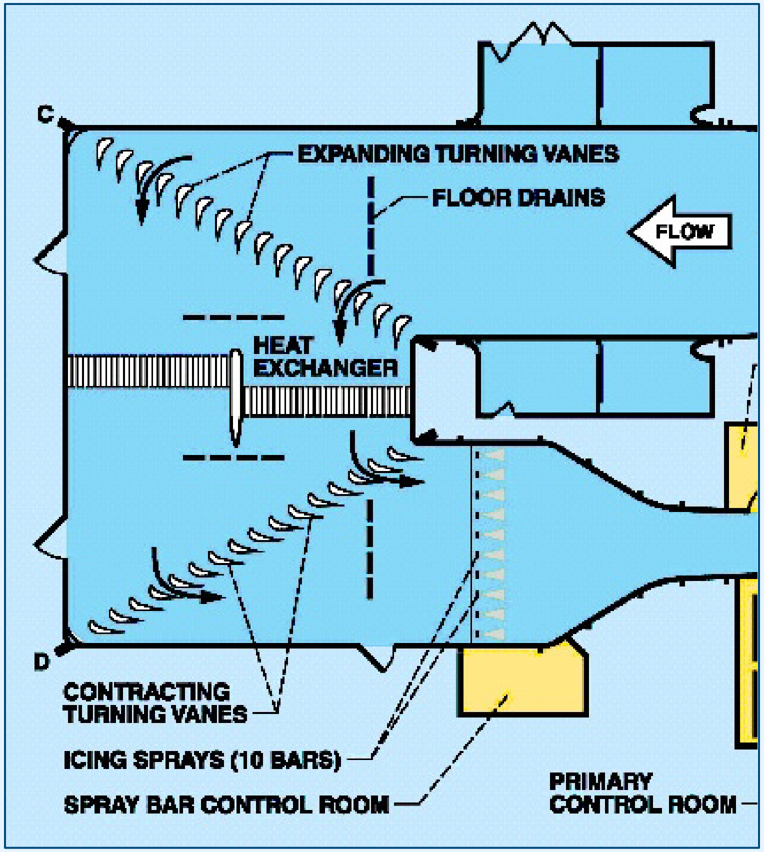
with Freon-12 (R-12)

W-shaped Heat Exchanger designed by Carrier Corp.



"Our greatest engineering feat." – Willis Carrier

2000 Flat Panel Heat Exchanger



- Very low turbulence
- Lowest temperature increased (refrigerant changed from R-12 to R-134A)

Motivation for 2011 Upgrade

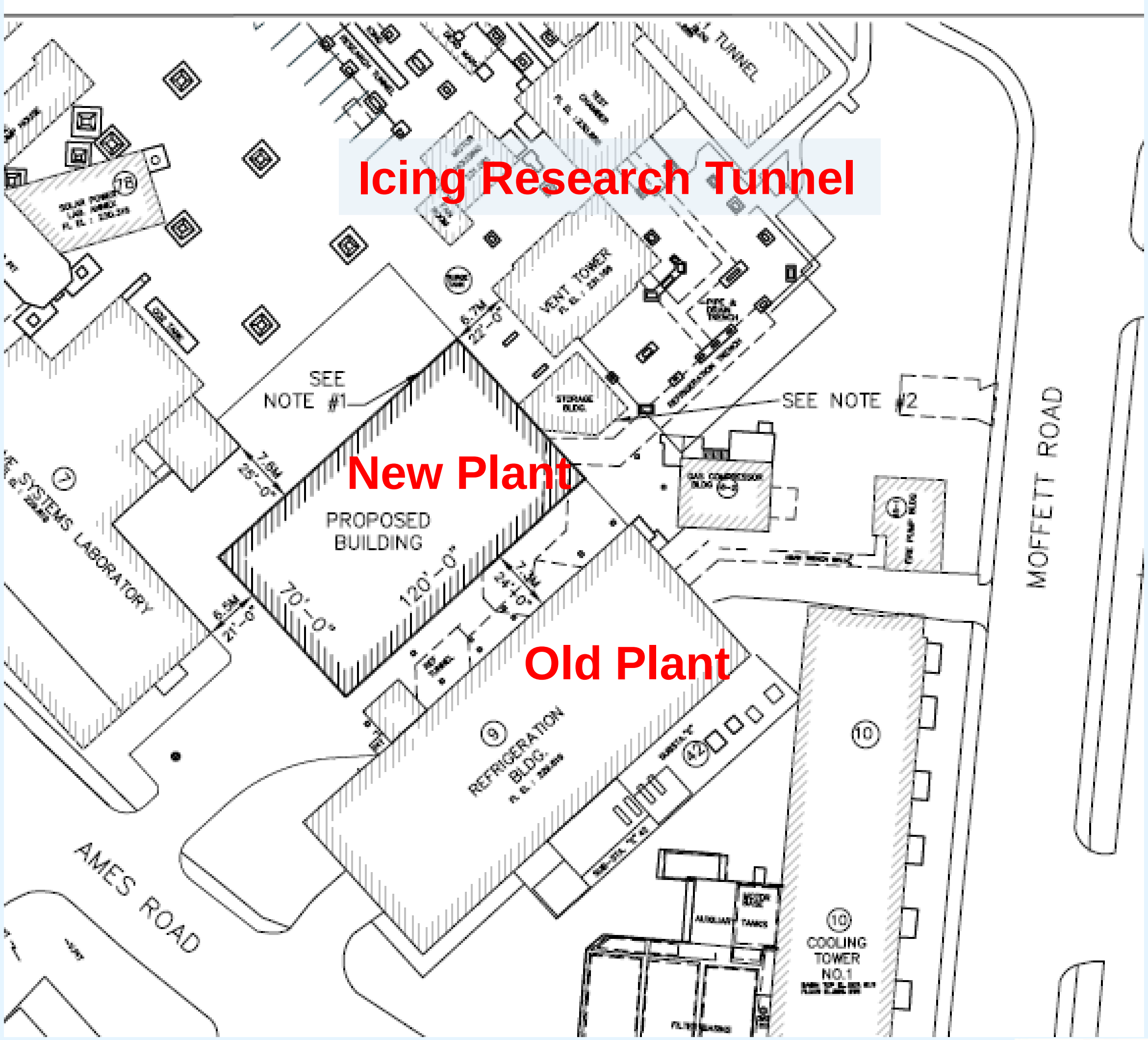
- Loss of lowest attainable static temperature
  - Migrated from -40 C to -27 C
- Ice crystal shedding off heat exchanger concern
  - Create uncontrolled test conditions at high speeds and cold temperatures.
- Maintenance & operation costs of 1940’s equipment in refrigeration plant.

Opportunity & Path Forward

- American Recovery and Reinvestment Act (ARRA) funding becomes available
- IRT determined to be a priority
- Design – Build delivery method
- Contract awarded to Jacobs Engineering, Inc.

Site of New Refrig. Plant Bldg

To minimize down time, NASA opted to build a new refrigeration plant.

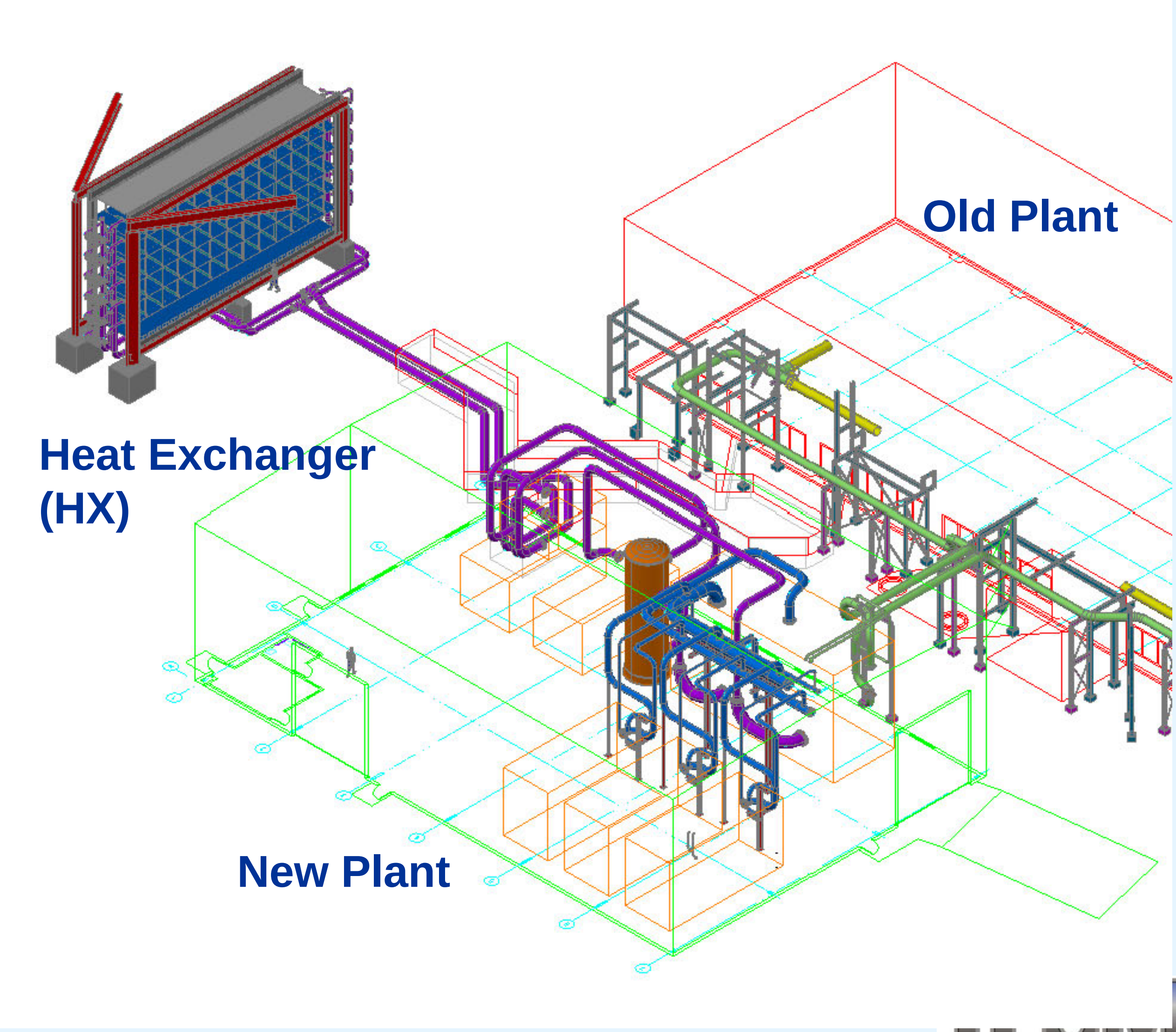


New Refrigeration Plant and HX

Schematic from Jacobs Engineering.

Jacobs design elements:

- two-fluid system
- staggered (not flat) panel heat exchanger.



Upgrade Objectives

✓ 1. Regain lowest attainable static temperature of -40 C.

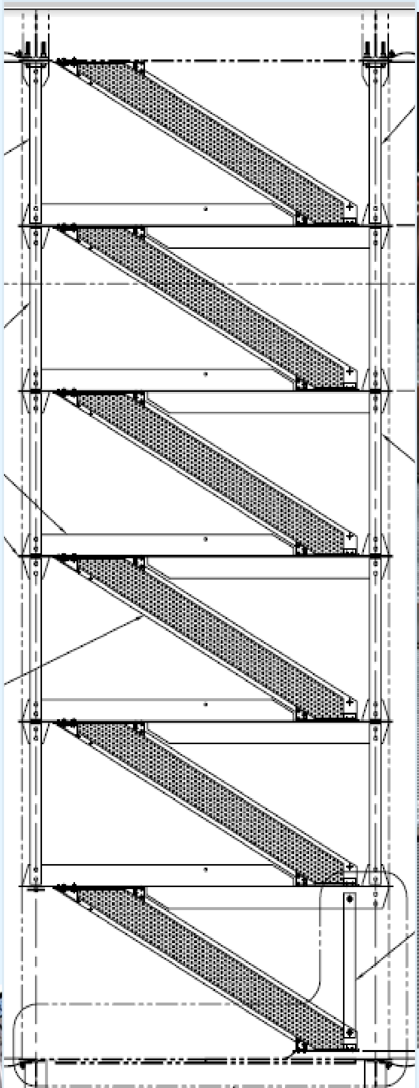
✓ 2. Eliminate or reduce ice crystal shedding off heat exchanger.

✓ 3. Significantly reduce costs and increase efficiencies in maintenance & operation.

Additional Improvements:

- Temperature spatial uniformity ±0.2 C
- Max air speed upto 350 kts (empty test section)

Final Upgrade Slide



Cloud Calibration

Bob Ide

Outline for Cloud Calibration

For both the Mod1 and Standard Nozzle sets,

Cloud Calibration Steps

1. Create/Document Cloud Uniformity
2. Drop Size (Pair, DeltaP)
3. Water Content (VTAS, Pair, DeltaP)

Goal: Generate a map of

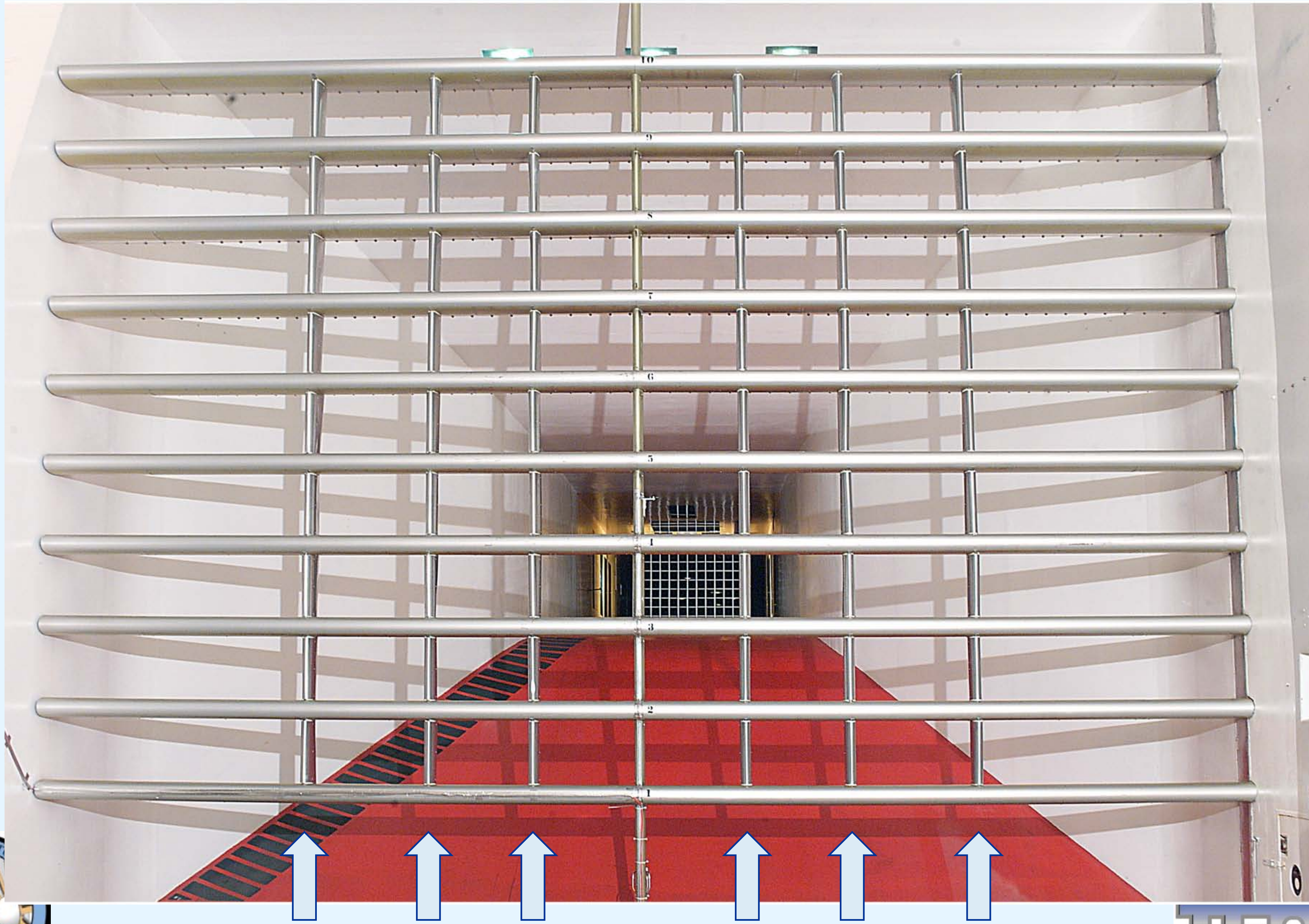
(VTAS, Pair, DeltaP) ⇨ (MVD, LWC)

Pair (psig) = spraybar atomizing air pressure
DeltaP (psid) = spraybar (water – air) pressure

Cloud Uniformity

Do we still need the struts?

Spray Bars with Struts



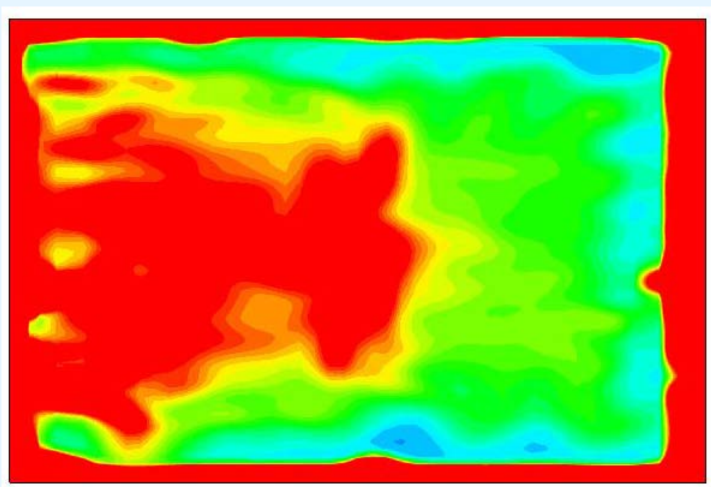
Test Facilities Operation, Maintenance & Engineering

K. Clark & E. Loth/UVA: Virtual IRT

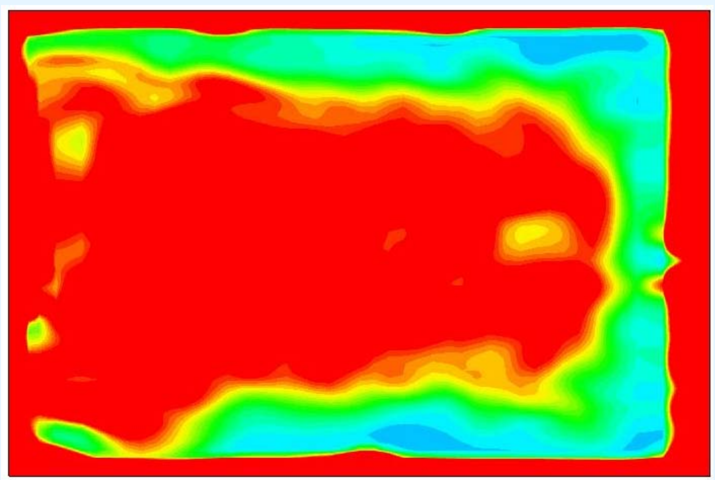
Provided guidance on whether or not the IRT needed the vertical struts on the spraybars to enhance cloud mixing.

Test Section Turbulence

Inner Wall

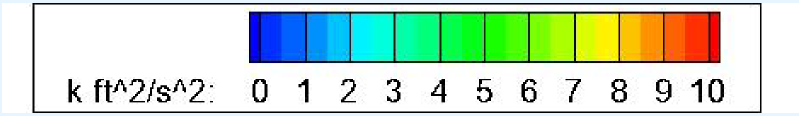


No Struts



With Struts

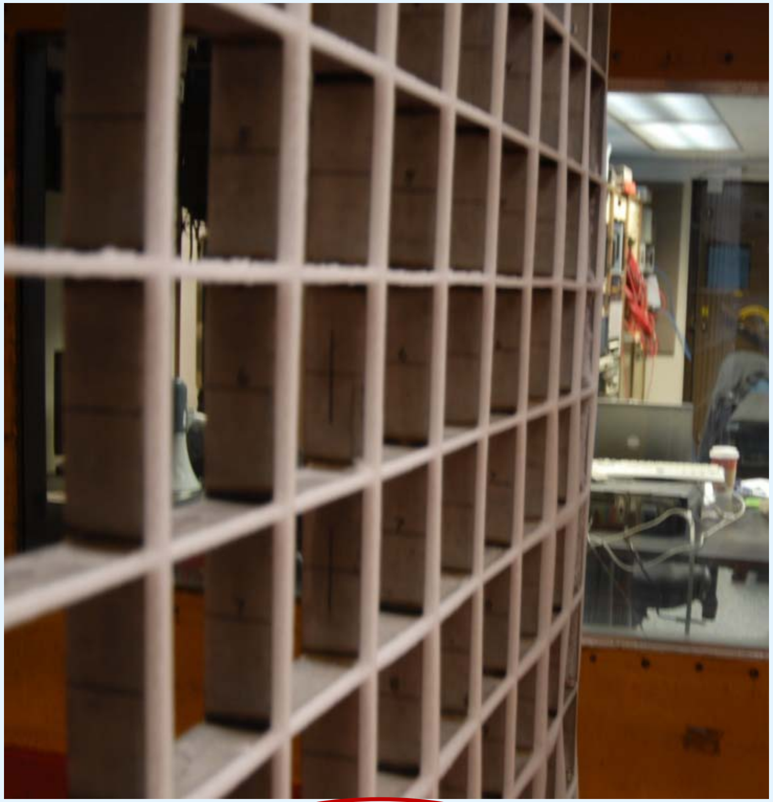
Outer Wall



Cloud Uniformity: Strut Effect

Outer Wall

Outer Wall



No struts

Struts

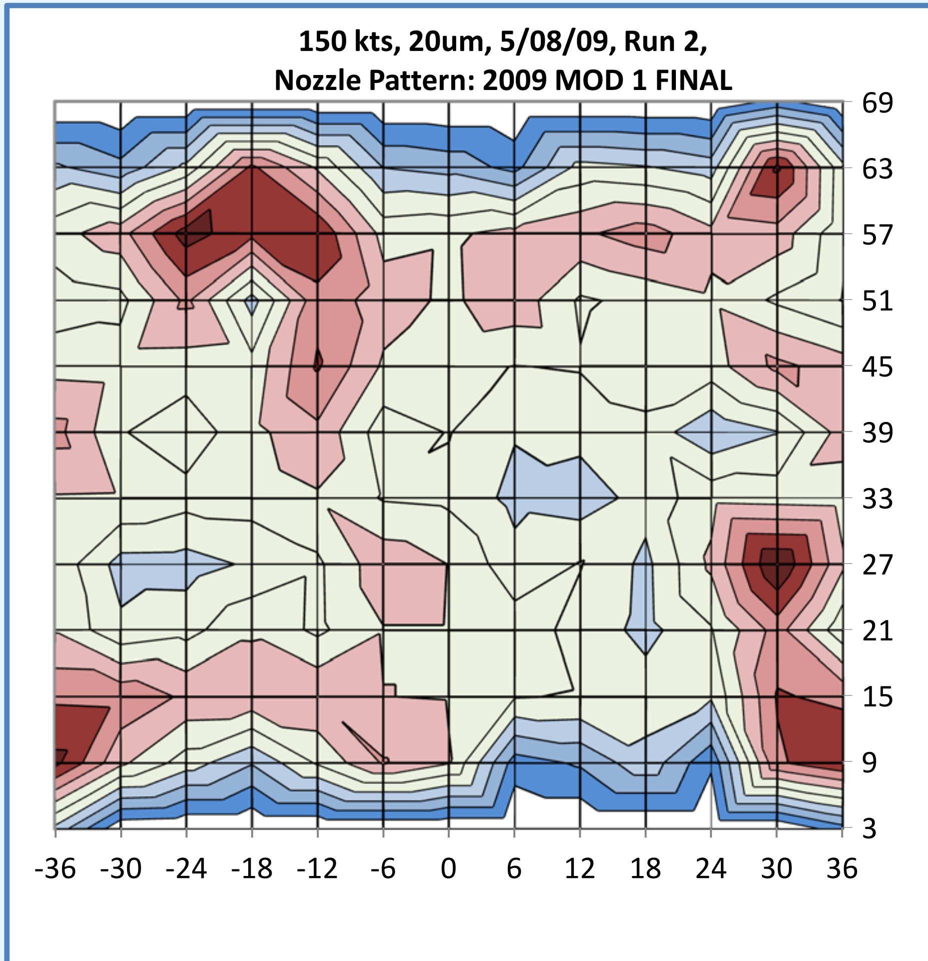
Ice accretion on the grid

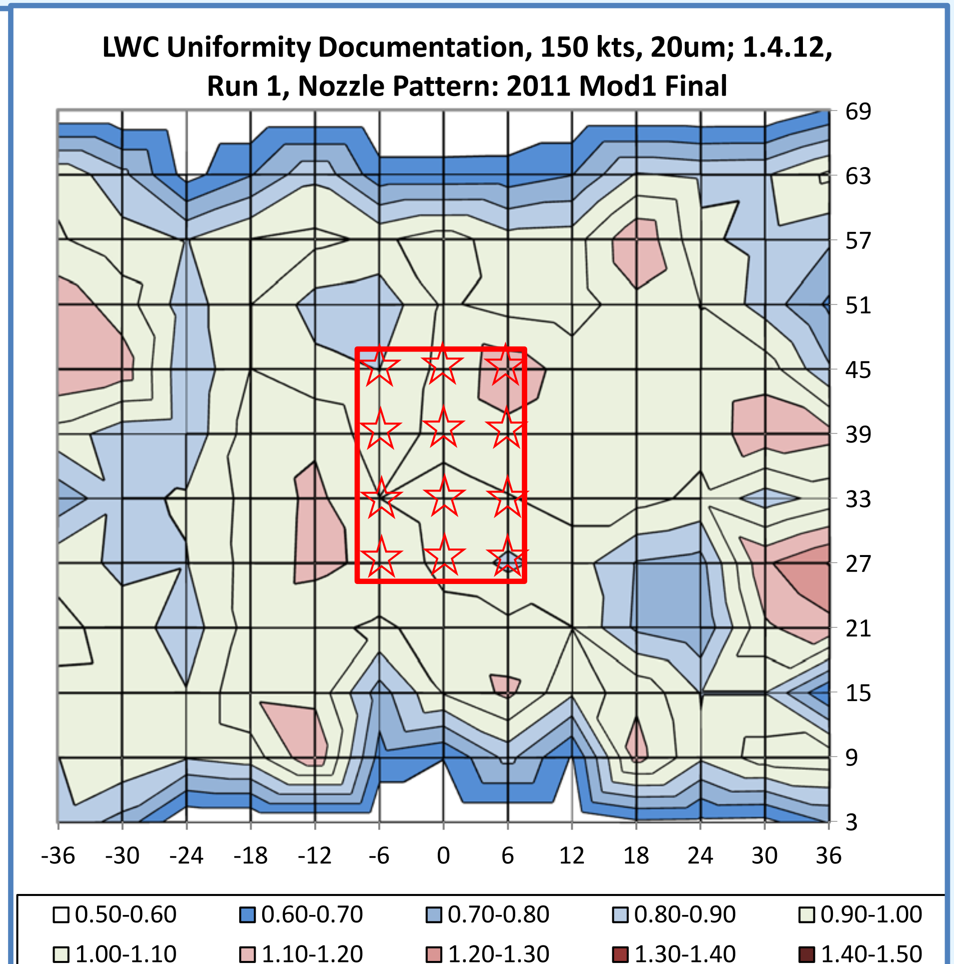
Cloud Uniformity

- Grid is 6x6 ft^2 with ½ x ½ ft^2 mesh
- Engineer turns nozzles on/off to optimize uniformity.
- Emphasis is vertical centerline ± 12 inches, where most models are located.
- Graphs are displayed as a ratio of the center 12 average
- Increment is ± 10% of the center average

Transfer Map

Uniformity Comparison: Mod1

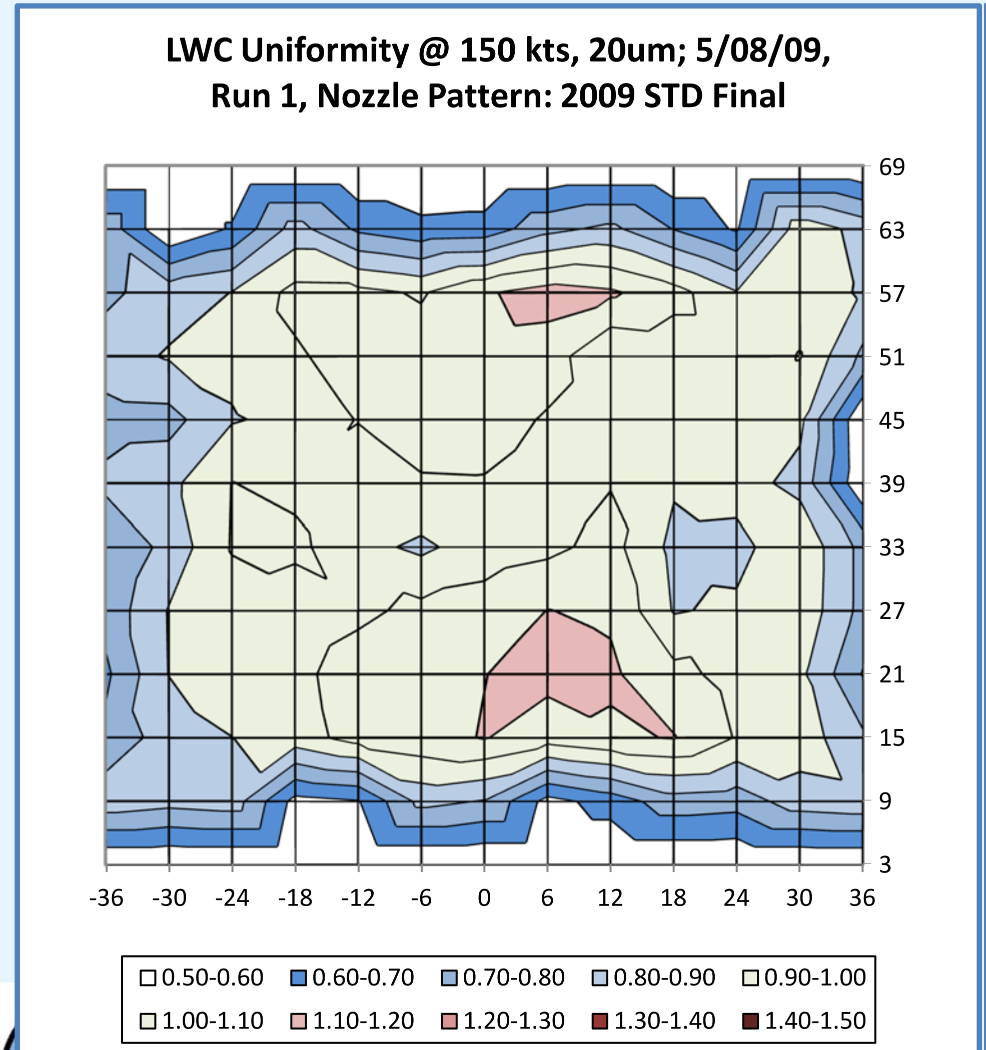




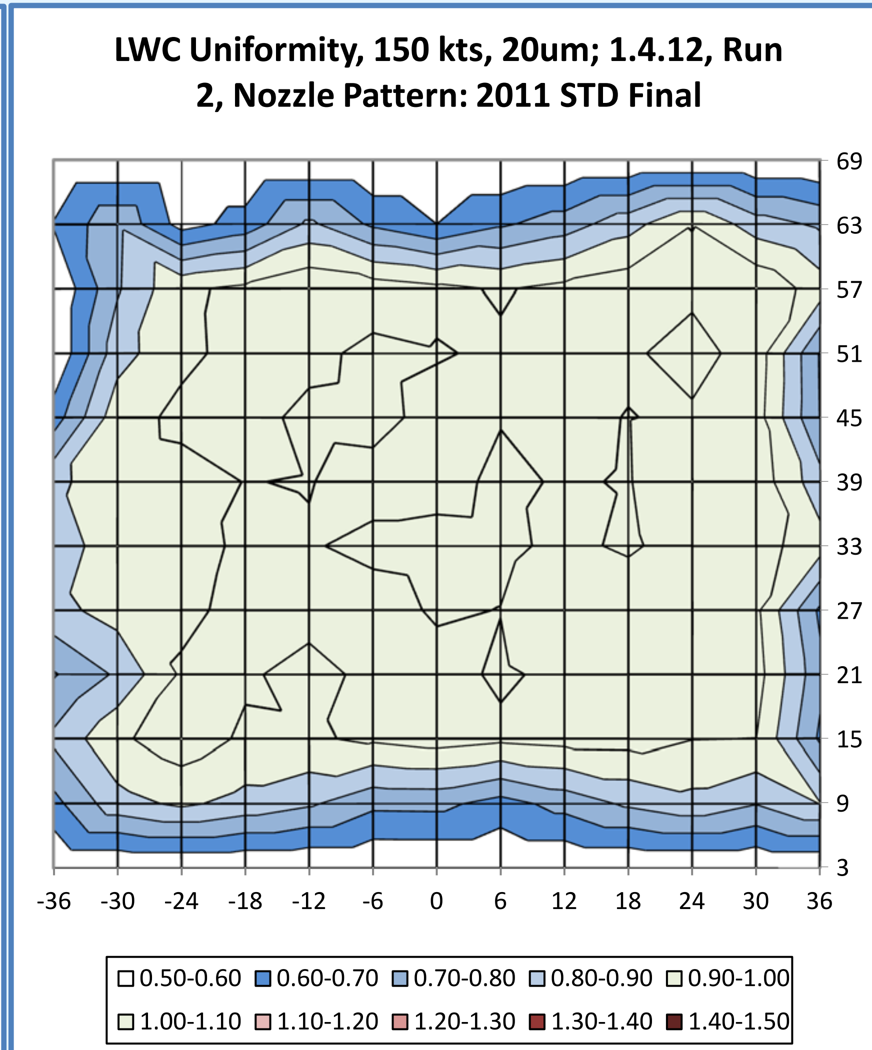
2009 (90)

2012 (75)

Uniformity Comparison: STD

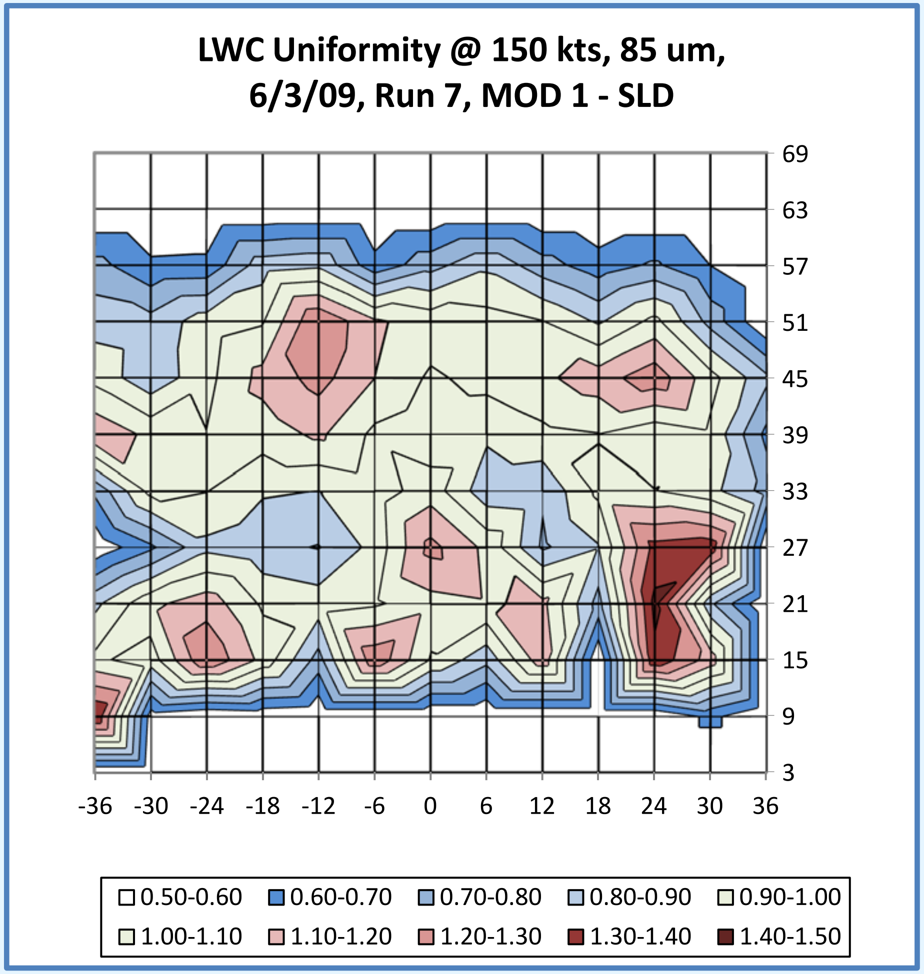


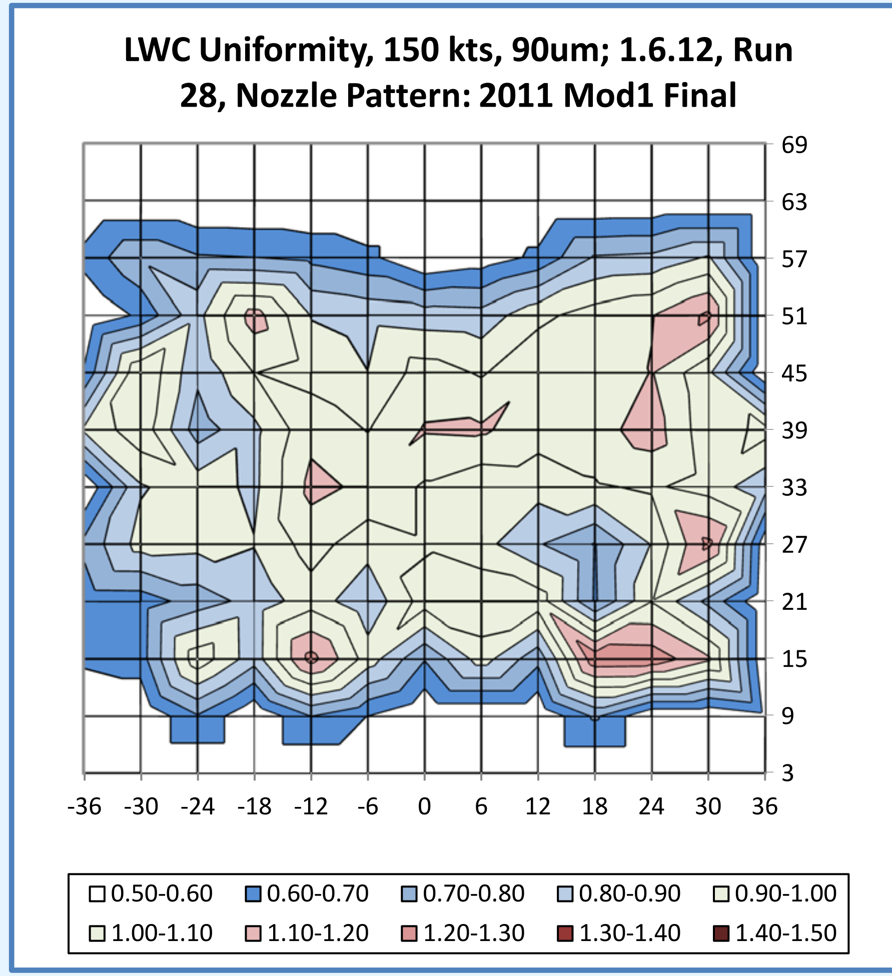
2009



2012

Cloud Uniformity: SLD case





2009

2012

Drop Size Cal – Prep

Historically use FSSP and OAPs

FSSP Ne-Ne laser would have been 12 years old

- Sent for repair/replace.

New probe came back unusable in IRT

- New laser beam dia. was almost 2x old laser.

SEA, Inc. shipped us an FSSP-ER – it broke in transit.

Installed IRT's new CDP probe

- Extreme electronic baseline drift.
- DMT fixed drift issue in time for next cal entry.

Attempted drop size cal w/ CDP Jun 4 – 8, 2012.

- Other communication issues uncovered.

Cal of smallest drops not successful.

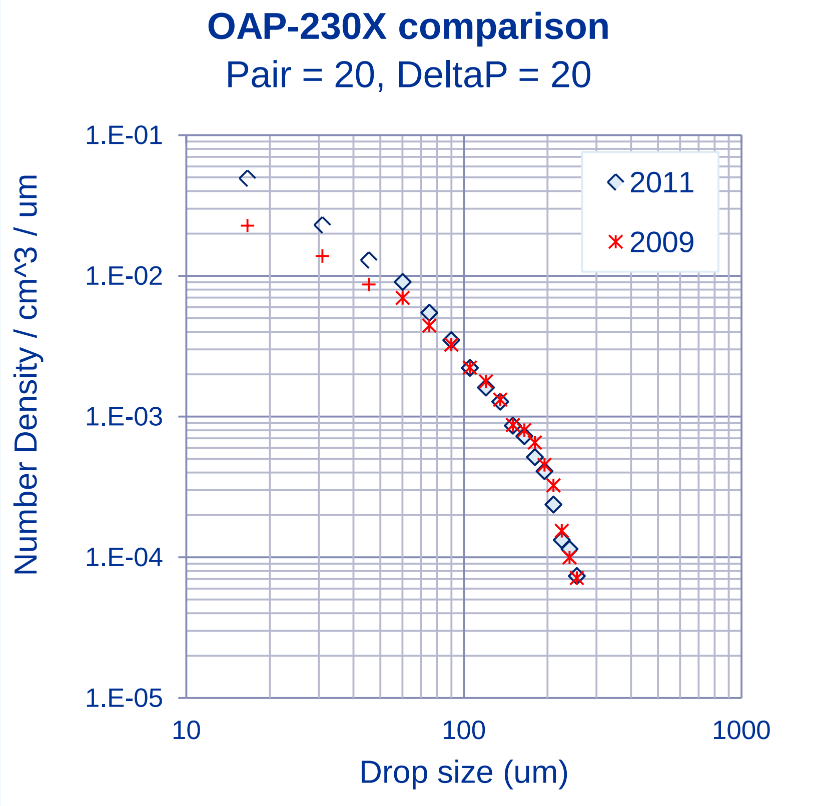
Drop Size Cal – Results

OAP-230X

FSSP, CDP (2 – 47 μm)
OAP-230X (15 – 450 μm)
OAP-230Y (50 – 1500 μm)

Did work just fine.

Results show no significant shift since 2009.



Drop Size Cal – Conclusion

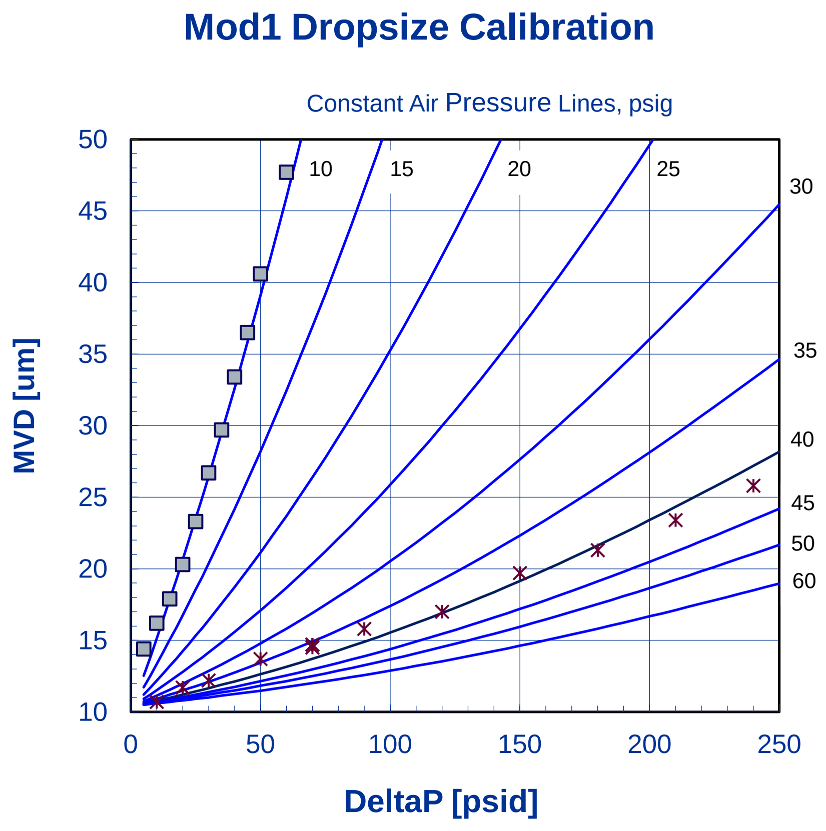
- Whereas the OAP showed no significant shift from 2009…
- Whereas we could not complete a calibration of the smallest drop size after two attempts…

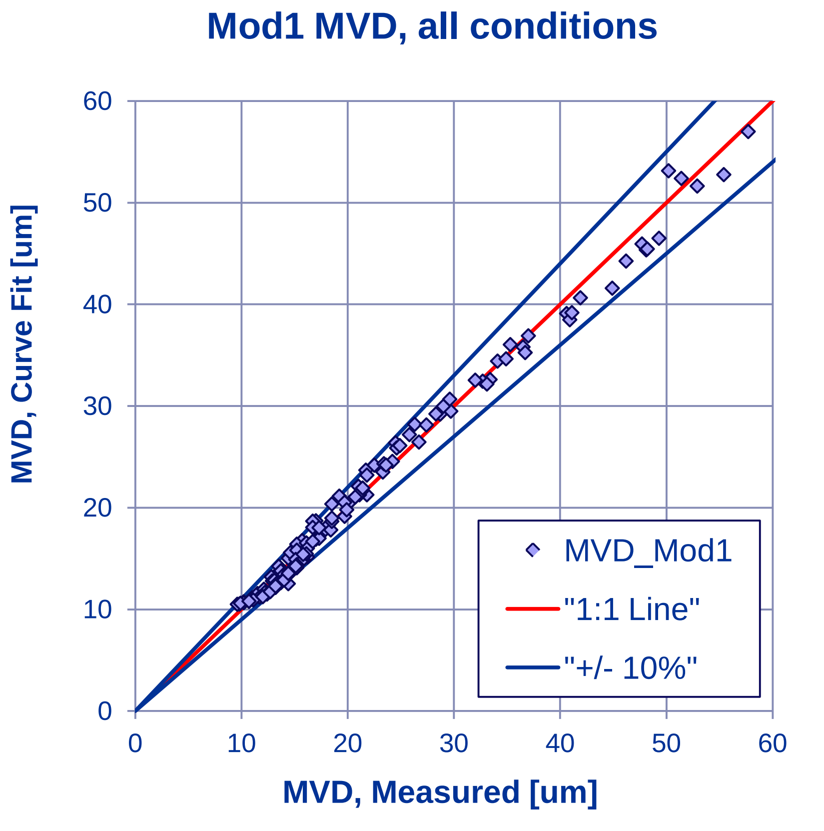
The Cal Team decided, as an interim measure, to stay with the

2009 Drop Size Cal

until the smallest drops could successfully be measured.

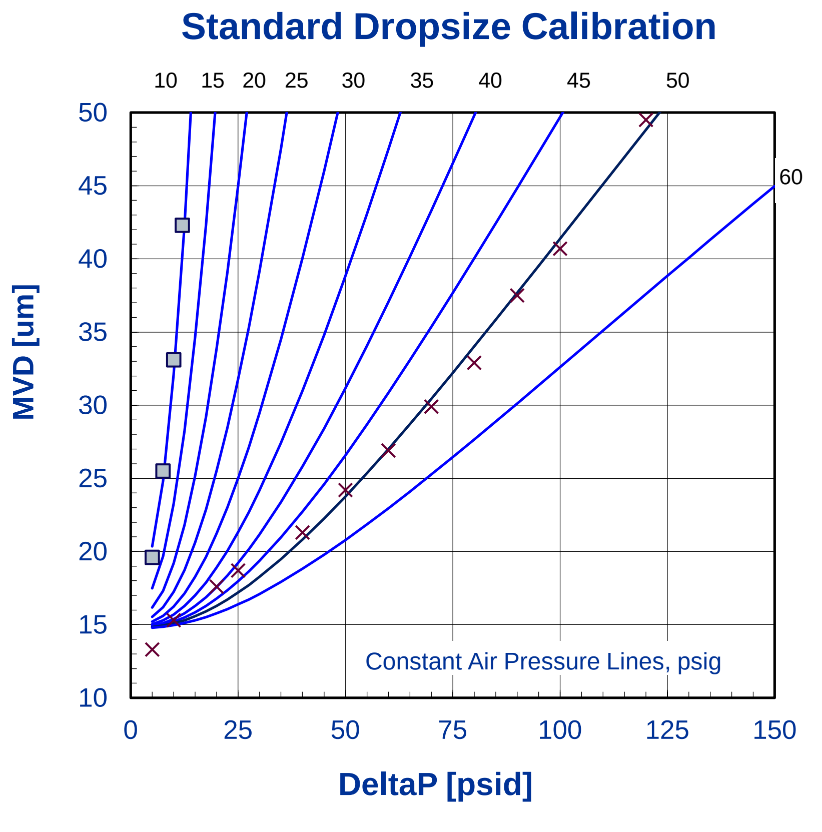
Mod1 Drop Size Cal

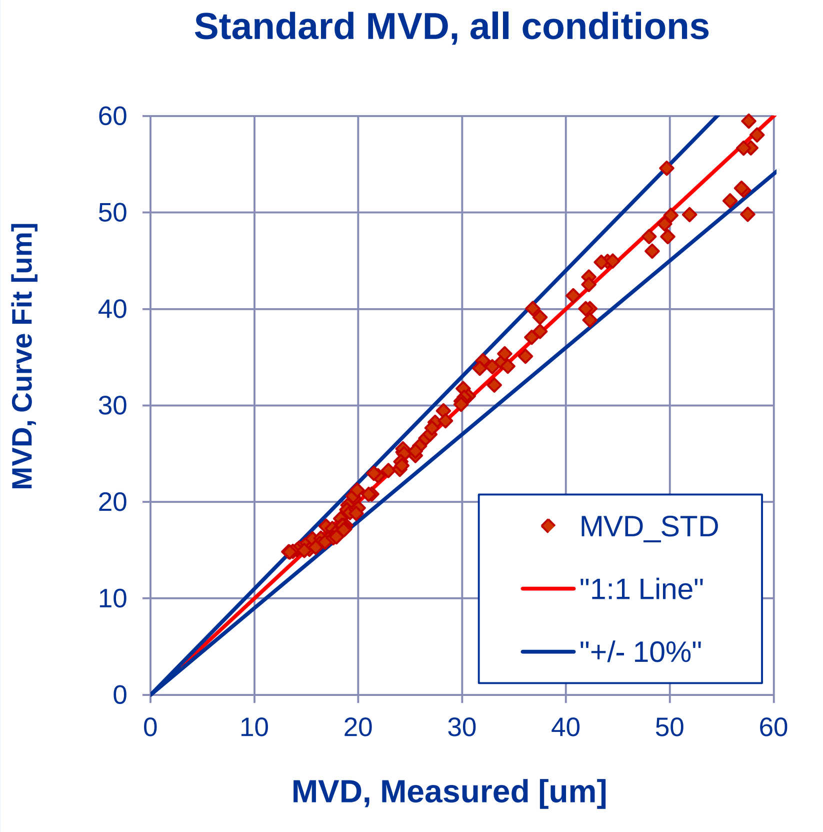




Test Facilities Operation, Maintenance & Engineering

Standard Drop Size Cal





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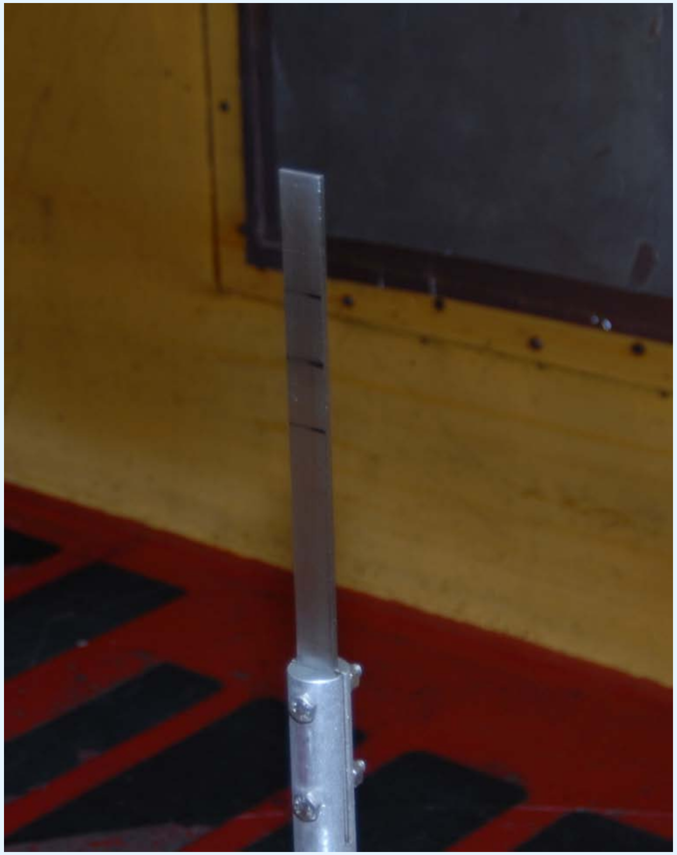
LWC Cal – Prep



Icing Blade
1980s? to 2012

SEA, Inc. Multi-Wire (SN 2022)
2009 to …

LWC Instrument Comparison

Blade *LWC = K(Pair, V)*√(DP)/V*

Blade responds accurately if

- droplets freeze on impact
- accreted ice shape does not have a significantly different collection efficiency

To support these assumptions,

- Accrete rime ice (colder temps, lower LWC)
- Smaller drop sizes (no splash)
- Shorter spray times

Experience in the IRT suggests the Blade responds well for

- LWC < 1.5 g/m^3 (not a hard limit)
- MVD < 60 um
- 50 ≤ V ≤ 200 kts

Heated Multi-wire

Measure power required to maintain wires at 140 C

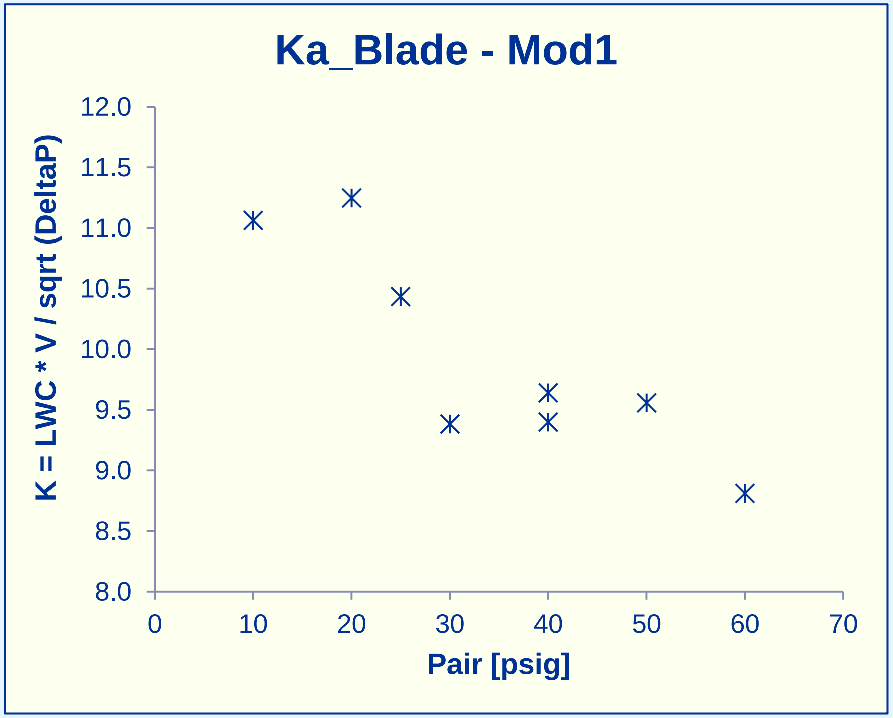
Can wait for steady state spray conditions

Responds to higher velocity, LWC and MVD ranges than Blade.

The half-pipe sensor measures TWC, the cylindrical sensors LWC.

LWC – Blade

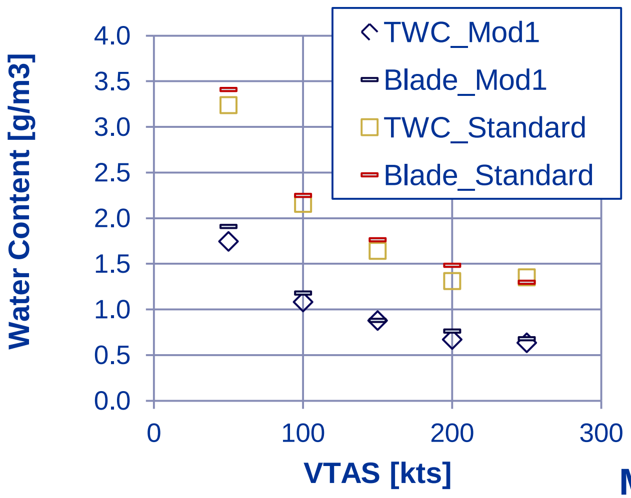
- Issues with Ovation spraying 2 sec longer (now fixed).
- Issues with ‘Spray On’ DeltaP transients (now fixed).



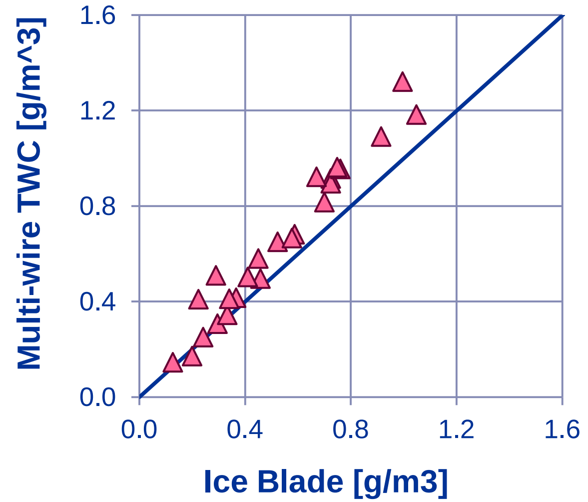
Too much scatter!

Blade vs Multi-Wire (Jan 2011)

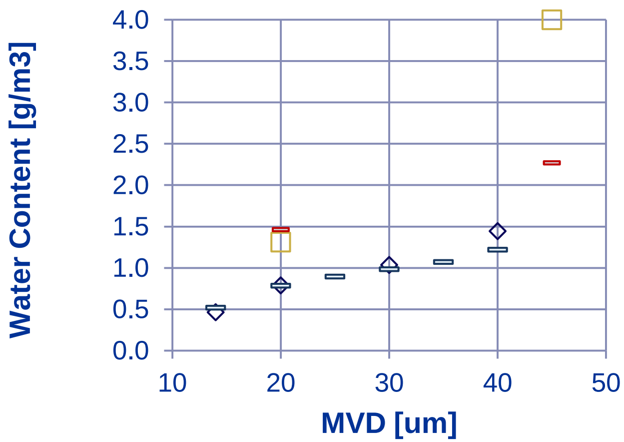
Multi-wire TWC vs Blade: Speed Effect at 20 um



Multi-wire vs. Blade: SLD Conditions

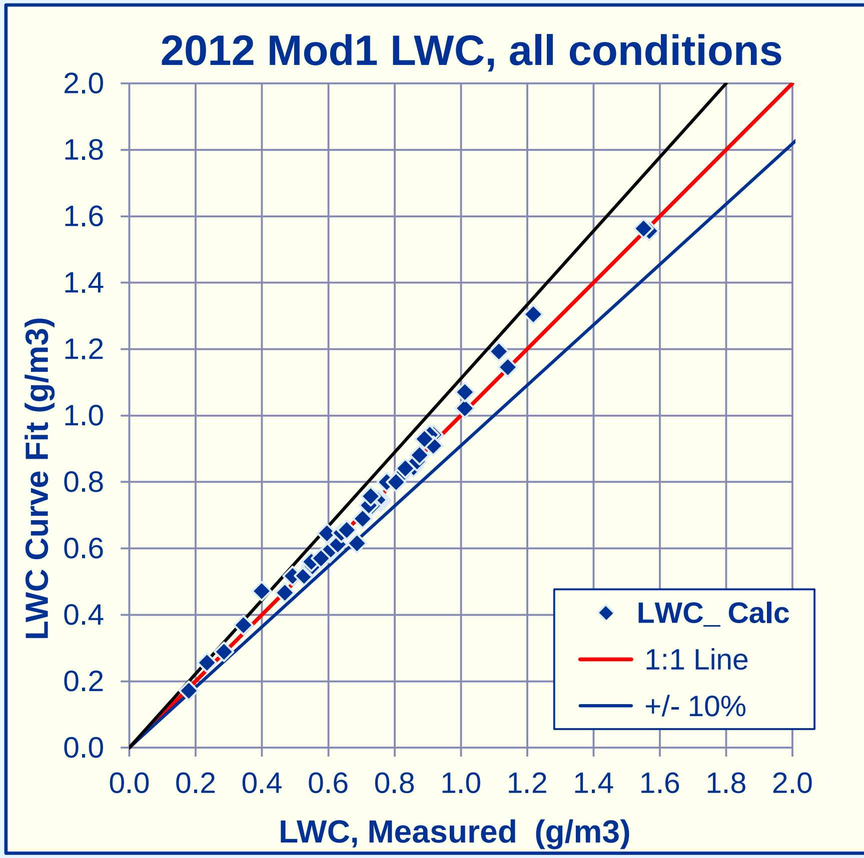


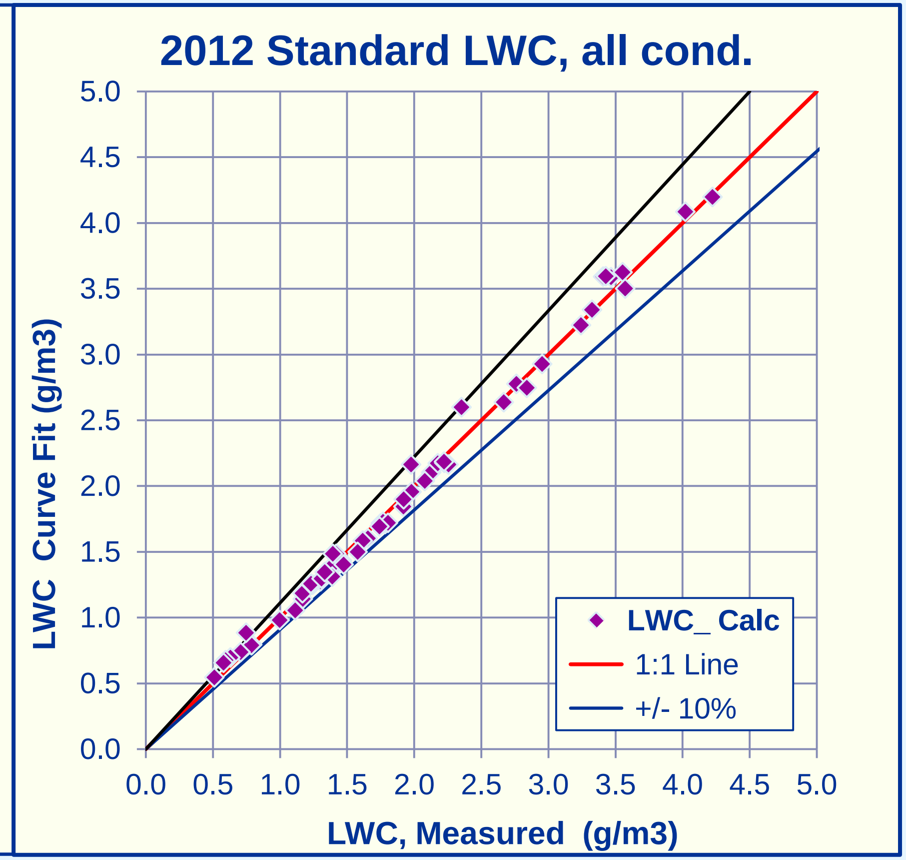
Multi-wire TWC vs Blade: MVD Effect, const. speed



Multi-wire sensitive to drop size effect not seen with Blade

LWC Results with TWC_2022

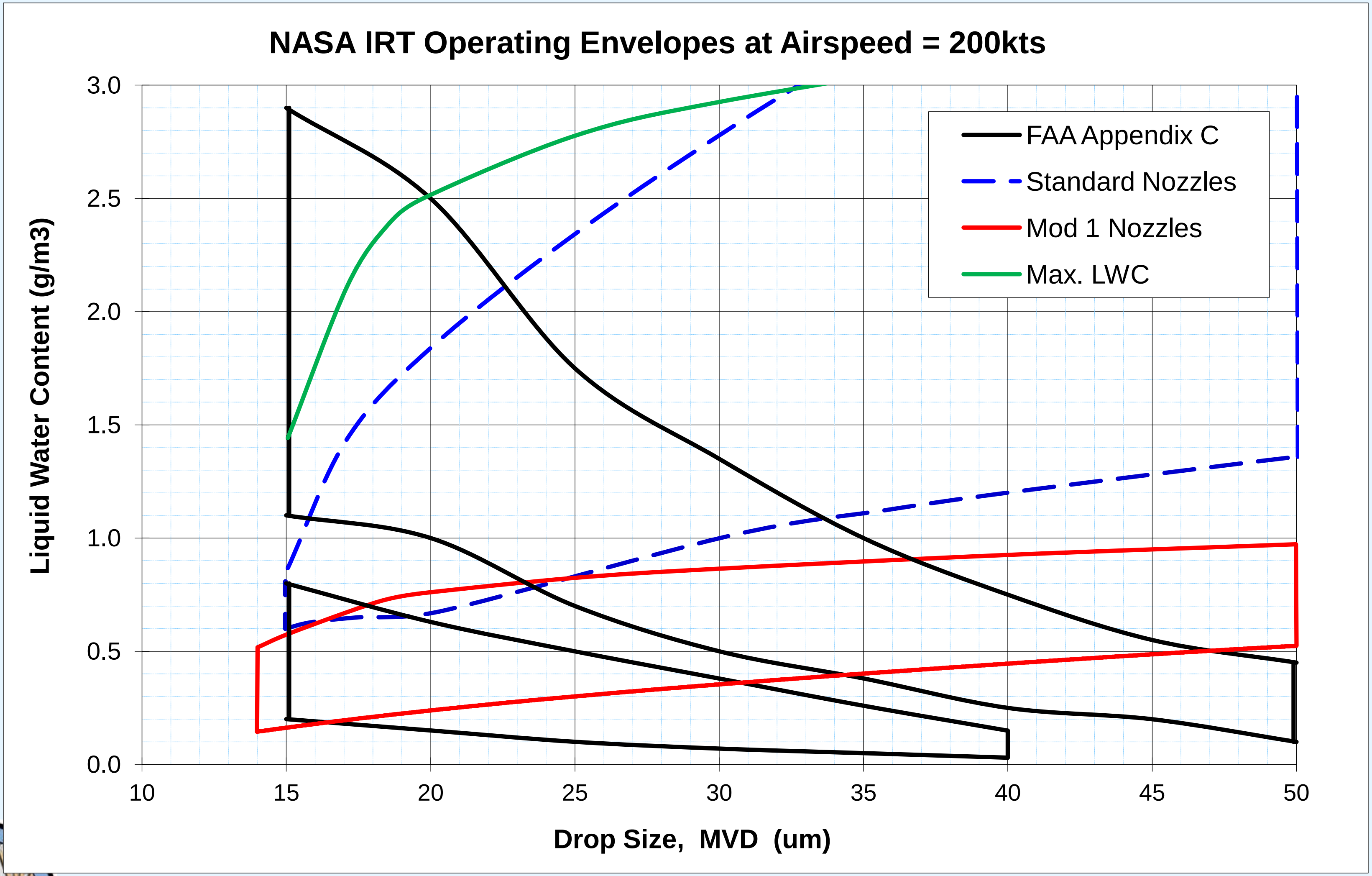




App C Envelope Expanded

- Better Mixing with new heat exchanger allowed us to use fewer Mod1 Nozzles: 75 in 2012 vs 90 in 2009.
- We were able to shift the Mod1 LWC 12 – 22% lower, closer to FAA App C targets.
- We kept the Standard Nozzles the same, so as to not lose the upper LWC end.

IRT Envelop at 200 kts



Spraybar Calculator

2012 IRT Calibration

2/22/2012

Input Icing Cloud Conditions

Tunnel Speed Knots	MVD µm	LWC g/m^3
200	20.0	0.70
Range 50 - 325 Knots	Range 14 - 50 µm	

Tunnel Speed mph	Tunnel Speed Knots
230.2	200.0

Max = 375 mph

Spraybar Settings and Calculated Output

Mod1 Nozzles

Pair	DeltaP	MVD µm	LWC g/m^3
45.6	197.1	20.0	0.70

Standard Nozzles

Pair	DeltaP	MVD µm	LWC g/m^3
11.1	5.4	20.0	0.70

Spraybar Settings / Icing Condition

Mod1 Nozzles

Tunnel Speed, kts	Pair	DeltaP	MVD	LWC	
200	45.6	197.1	20.0	0.70	242.70
	[10 - 60 psig]	[5 -250 psid]			

Standard Nozzles

Tunnel Speed, kts	Pair	DeltaP	MVD	LWC	
200	11.1	5.4	20.0	0.70	16.50
	[10 - 60 psig]	[5 -150 psid]			

Test Facilities Operation, Maintenance & Engineering

SLD Spraybar Calculator

2012 IRT SLD Calibration

5/7/2012

Input SLD Icing Cloud Conditions

Tunnel Speed Knots	MVD µm	LWC g/m^3
200	200.0	0.50
Range 100 - 250 Knts	Range 18 - 250 µm	

Spraybar Settings and Calculated Output for SLD

Mod1 Nozzles w/ Pair < 8 psig

Pair	DeltaP	MVD µm	LWC g/m^3
2.1	28.5	200.0	0.50

Spraybar Settings for SLD Conditions

Mod1 Nozzles

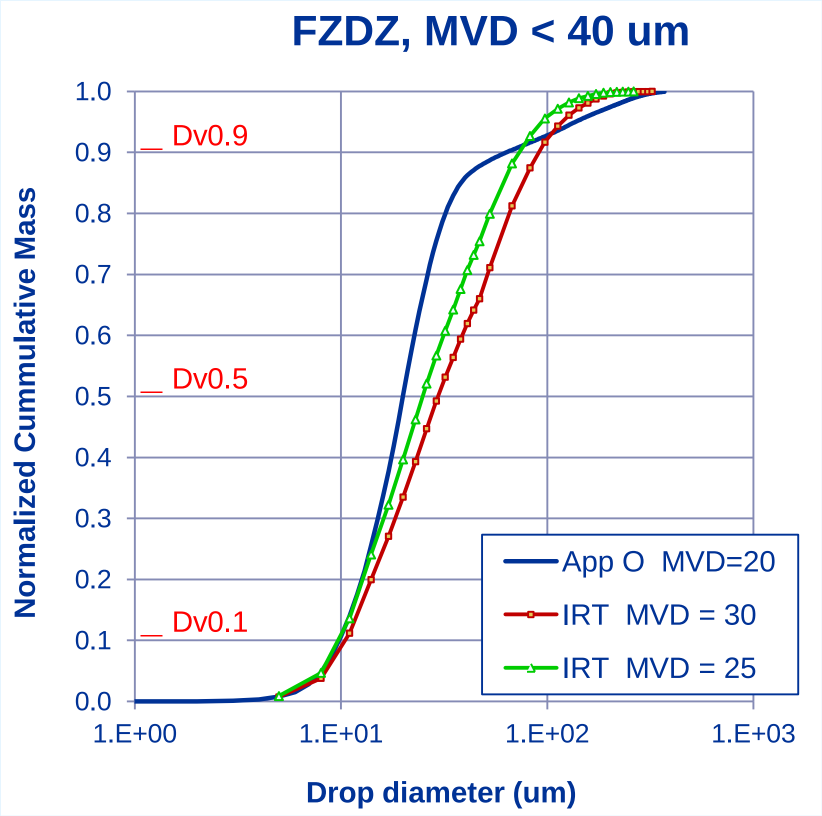
Tunnel Spd, kts	Pair	DeltaP
200	2.1	28.5
	[2 - 8 psig]	[5 -50 psid]

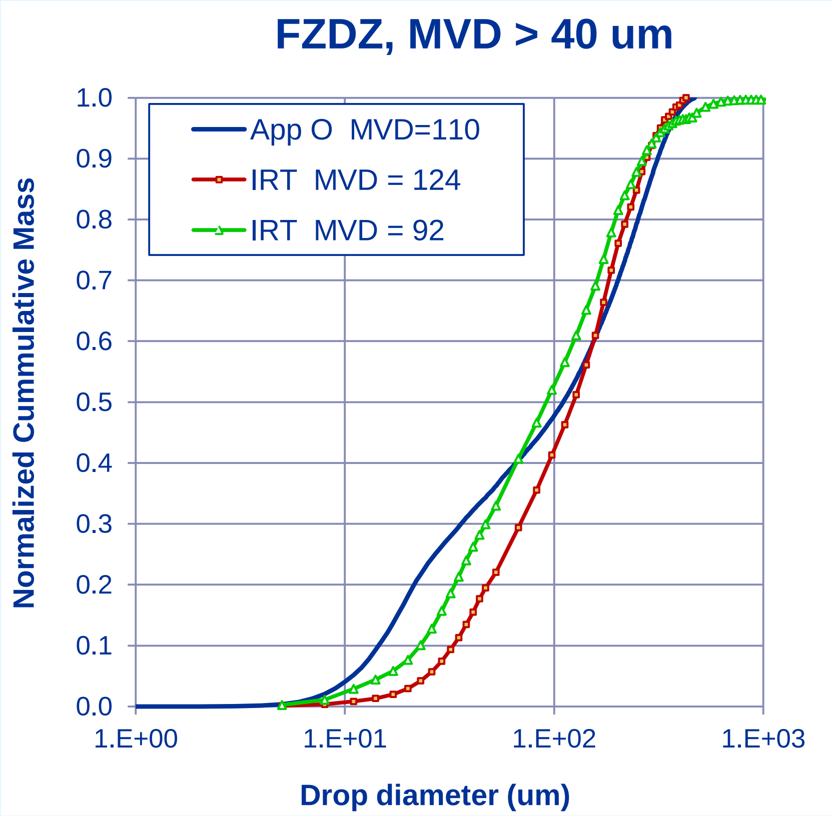
SLD Icing Condition

MVD	LWC
197.4	0.50

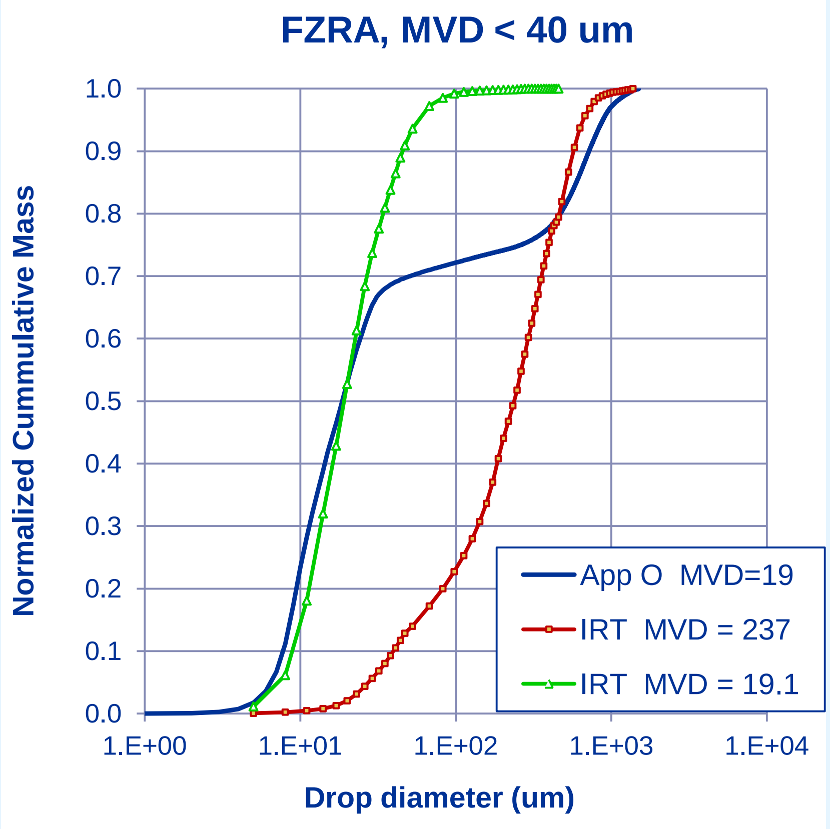
For this worksheet, "SLD" is defined as nozzle atomizing air pressures, Pair, between 2 and 8 psig.

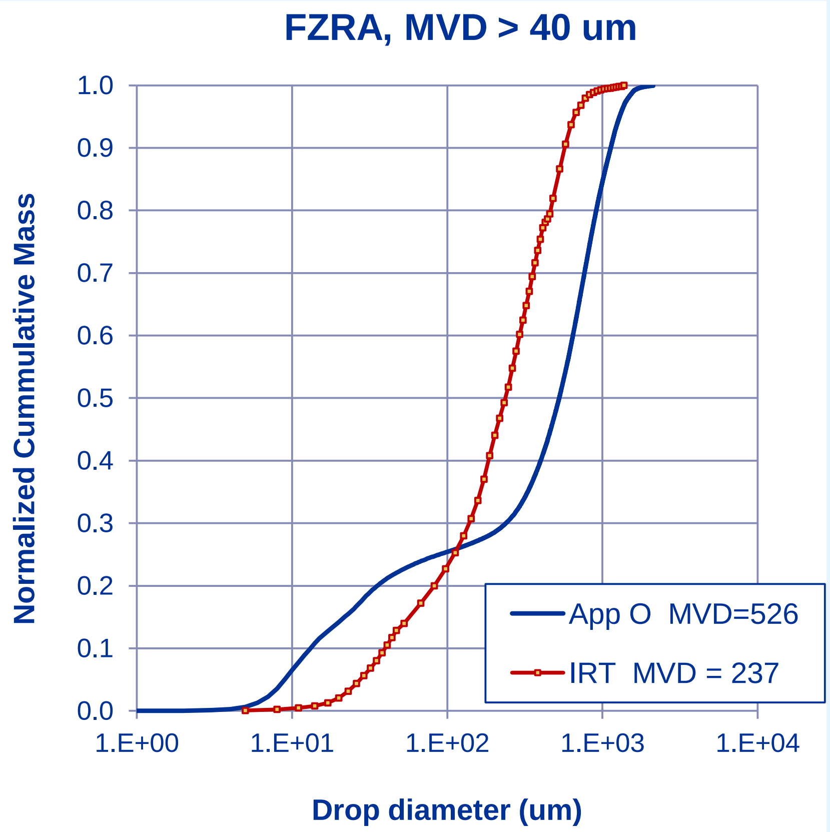
Freezing Drizzle & IRT



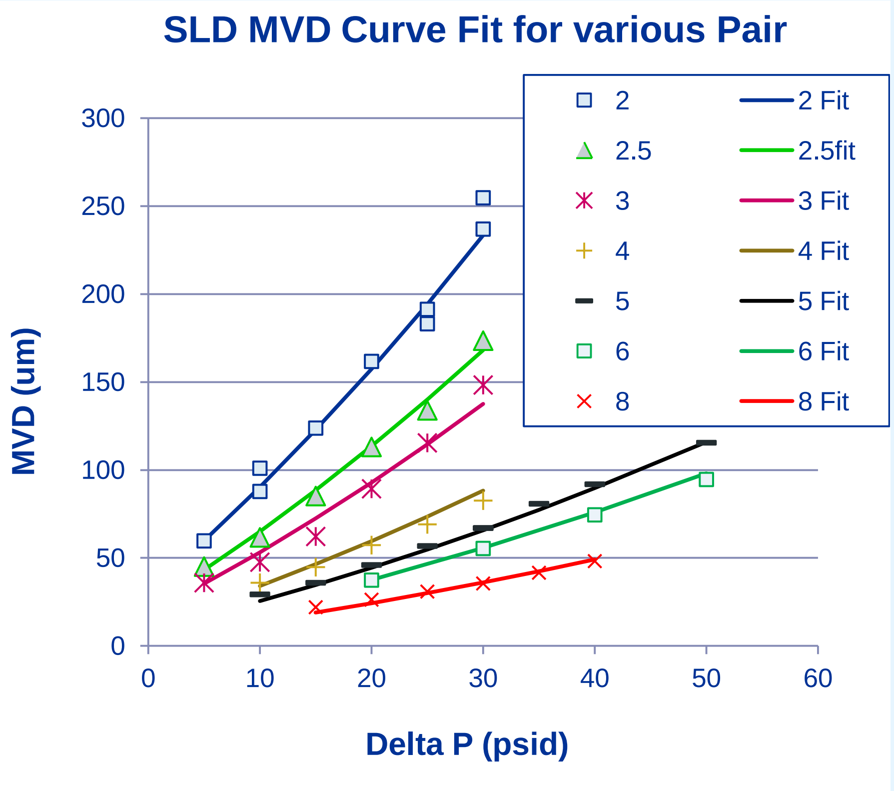


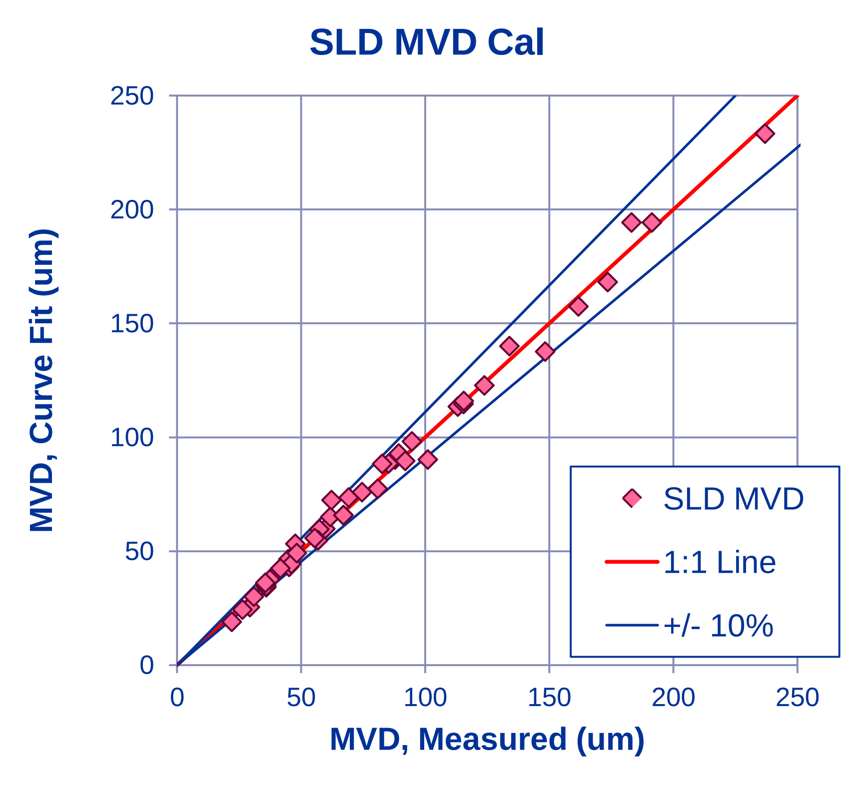
Freezing Rain & IRT





Pair<10 psig SLD MVD Curve Fits





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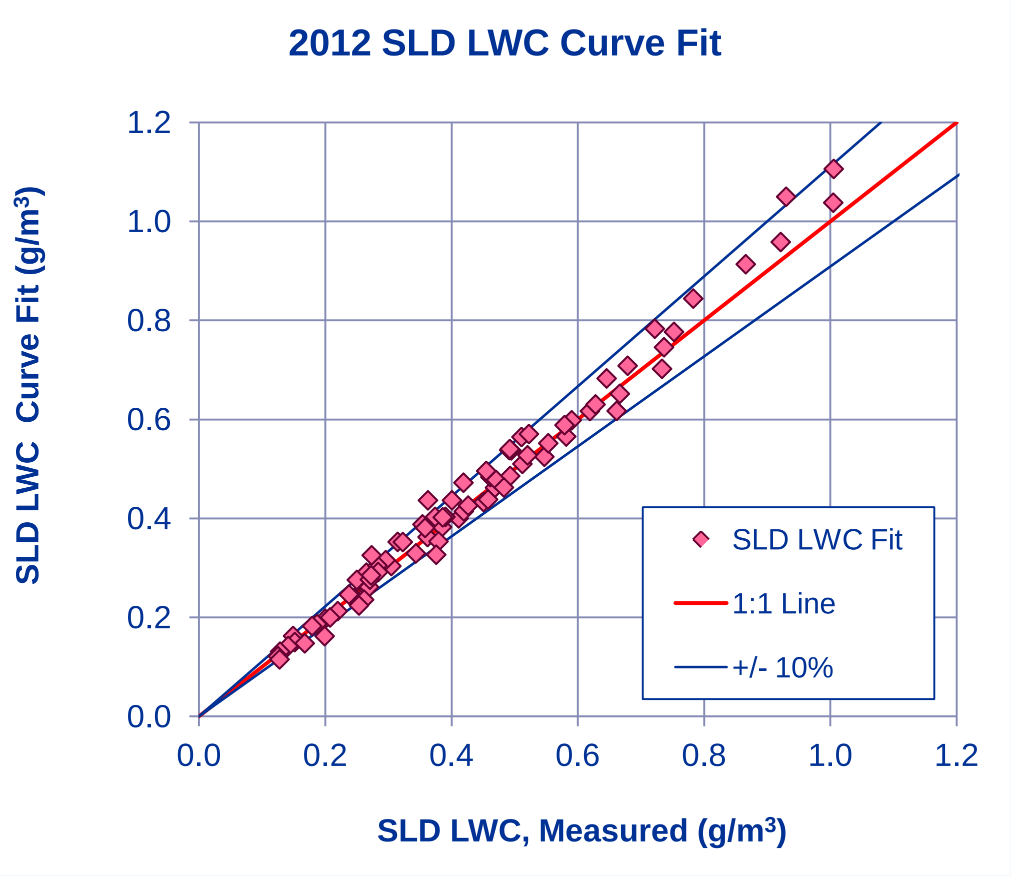
Pair<10 psig SLD LWC Curve Fit



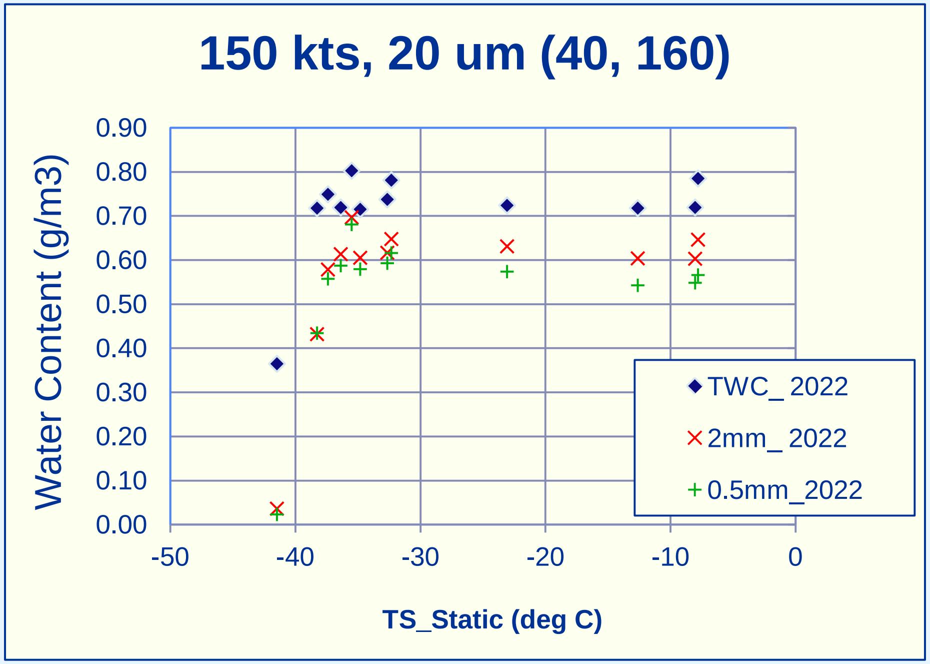
Ice Crystal Generation

Ice Crystal Shedding from HX (Spray Off)

- We DO shed ice crystals off HX with ramp to high speeds at cold temps.
- This DOES dissipate in time (< 5 min). Judy's visual of D-Corner matched the Multi-wire signal.

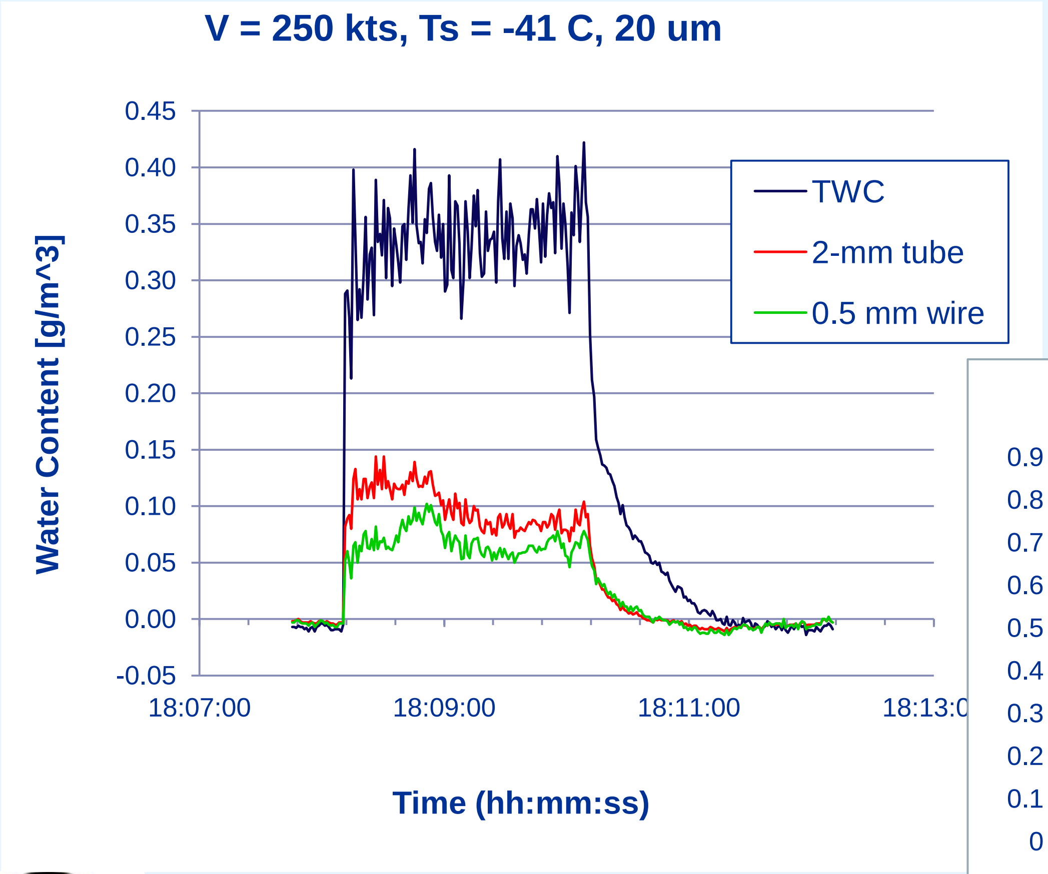
Droplet Freeze-out

- At Tstatic ≈ - 40 C we freeze-out the supercooled liquid water droplets.
- Freeze the Bars, too.
- The exact border is a fn of (VTAS, Pair, …).

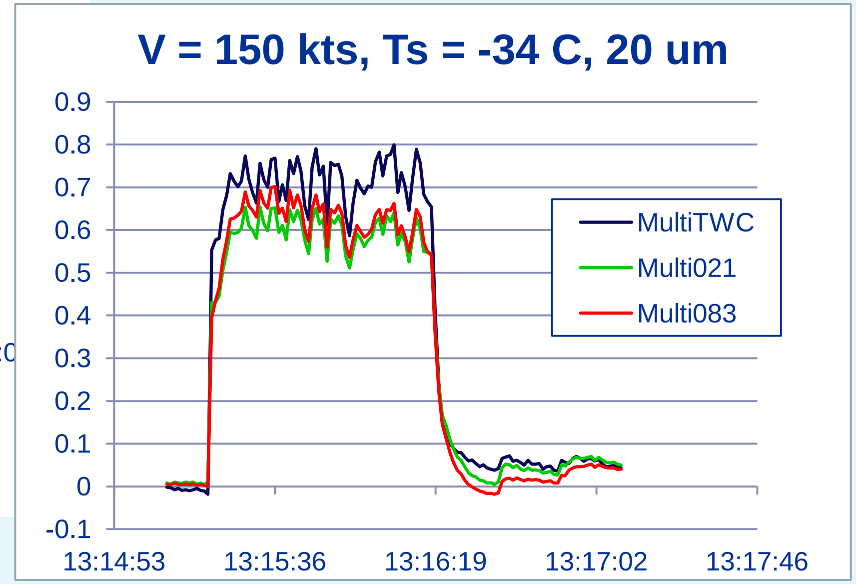


Ice Crystal Generation

Typical Multi-wire response in mixed phase environment.



Typical Multi-wire response in pure liquid environment.



Concluding Thoughts

- Objectives for new refrigeration plant and heat exchanger were successfully met.
  - Static Temperature down to -43C
  - More efficient testing and operations
  - Ice crystal shedding ‘managed’

- Cloud LWC Uniformity improved over 2009
  - With fewer nozzles

Concluding Thoughts

- MVD calibration:
  - Using 2009 drop size cal until FSSP/CDP instrumentation issues resolved.
  - MVD curves look great.
- LWC calibration:
  - Range increased with instrument change from Blade to Multi-wire.
  - Dropped Mod1 LWC curve 12 - 22% to better fit App C lower limits. Standard LWC unchanged.
  - LWC = fn(V, DeltaP, Pair *and MVD*)
  - LWC curves look great.

Special Considerations

Appendix O –

- Can match some features of : FZDZ and FZRA, MVD < 40 um.
  - Will likely never match FZRA, MVD > 40 um
  - Which features are important?

Special Considerations

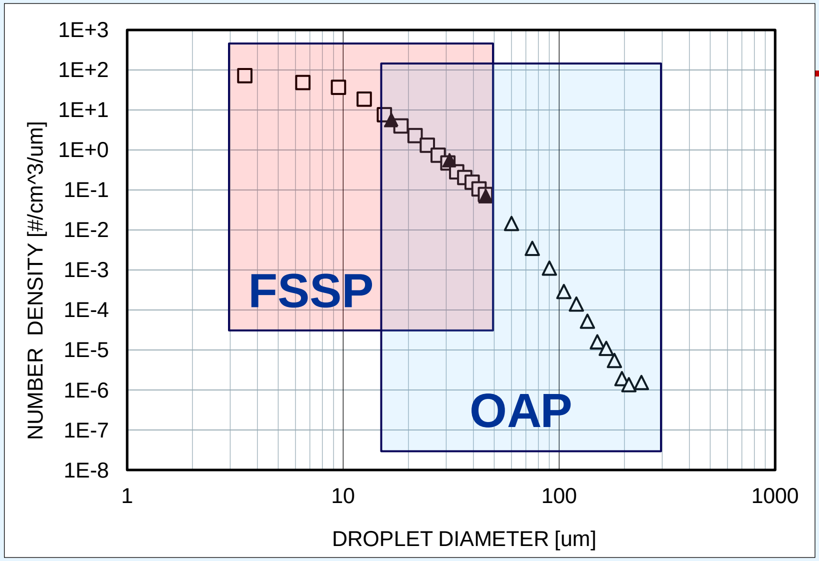
Ice Crystals –

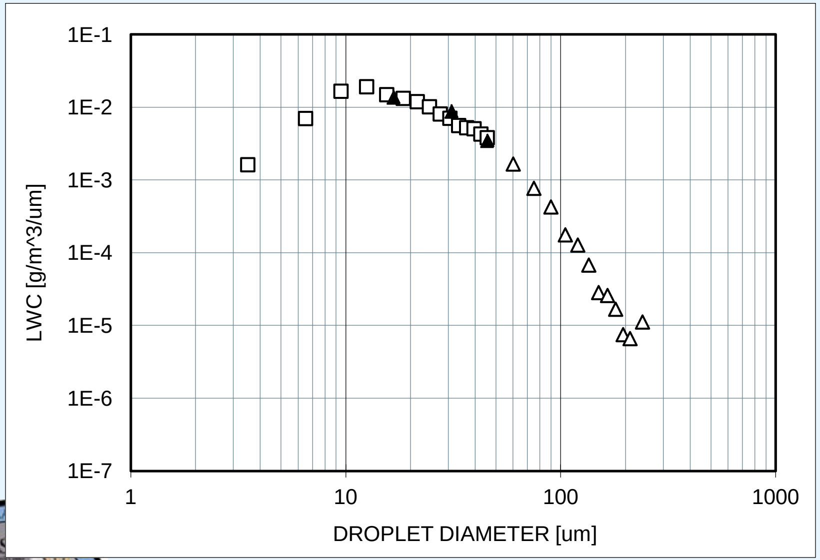
- Mostly managed, with caveats:
  - Beware ice shed after speed ramp at very cold temperatures (< 5 min)
  - Beware recirculating (?) ice crystals at very cold temps
- Can *possibly* spray a (somewhat) calibrated ice crystal cloud. (Pending successful modification of spray bars.)

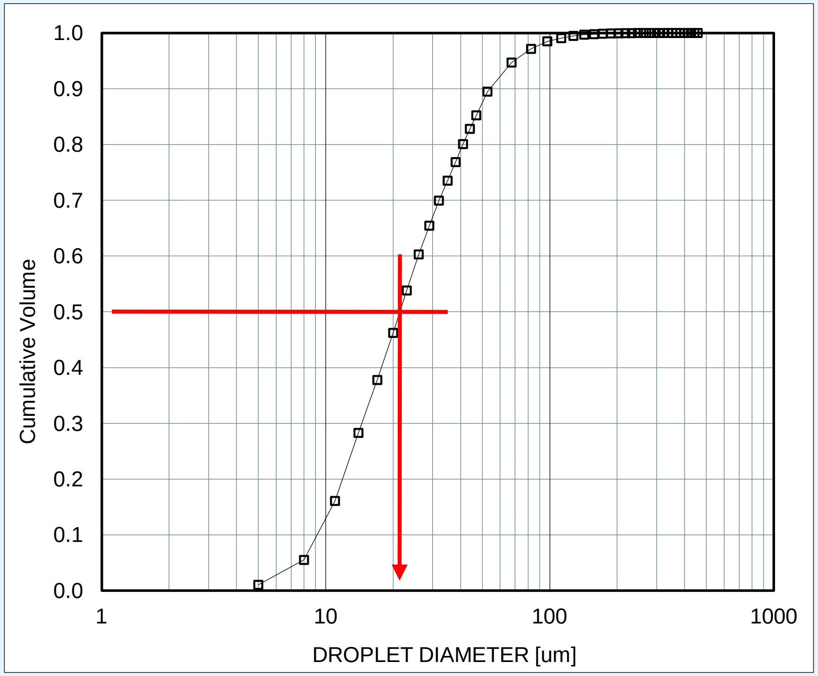
Questions?


ICING RESEARCH TUNNEL
NASA
Glenn Research Center
Cleveland
IRT
Advancing aircraft safety since 1944
WE FREEZE TO PLEASE
M–0973–1
Sep 02

1D Histogram Data Processing

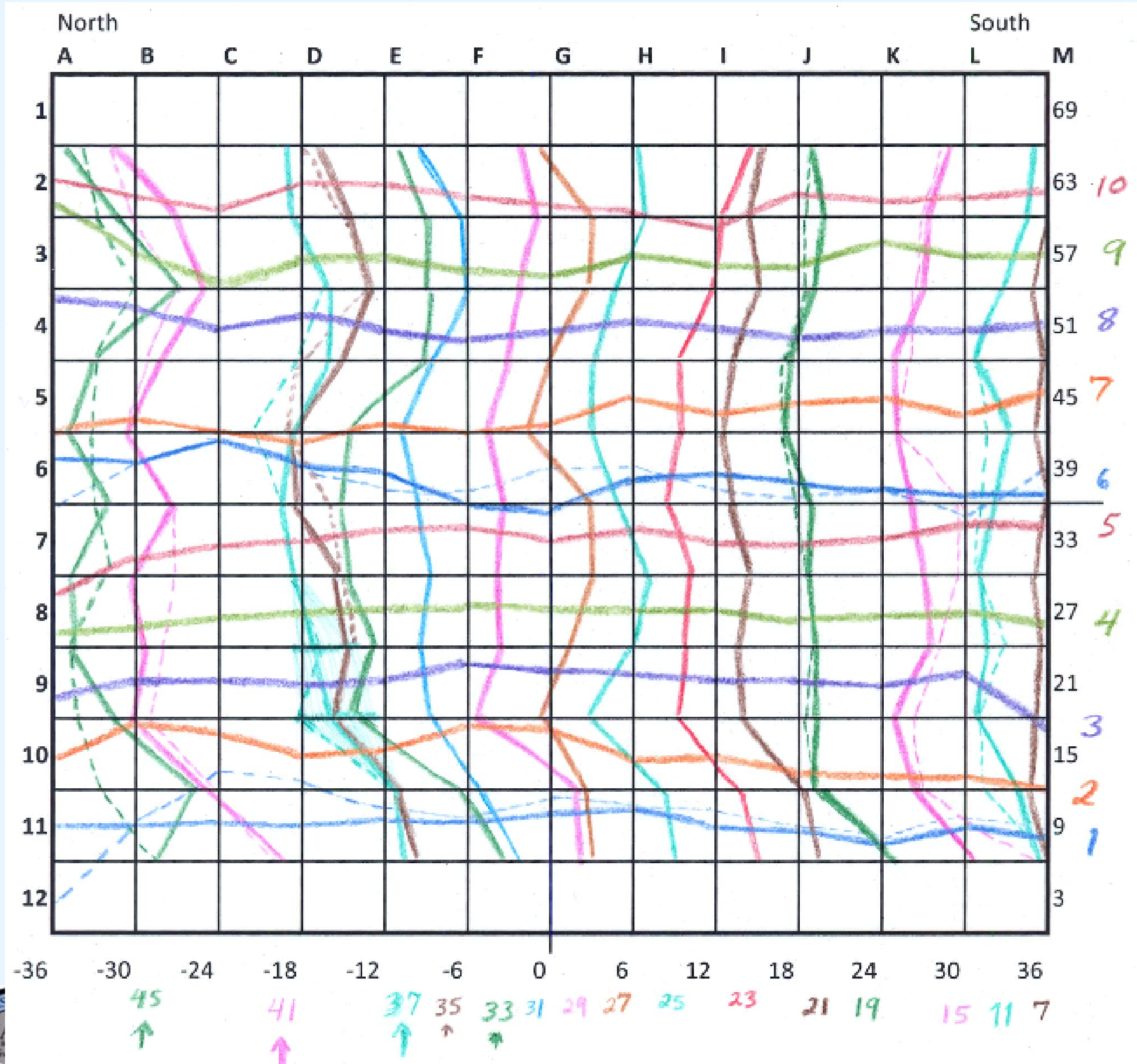






Calculate MVD

Nozzle transfer map



- Sprayed individual rows and columns of nozzles (in sets of 2 or 3) and recorded where the corresponding peaks of ice accumulation on the grid.
- Mapping these rows and columns on top of each other gives an idea where each nozzle's spray ends up in the test section

Return