

An Assessment of the Icing Blade and the SEA Multi-Element Sensor for Liquid Water Content Calibration of the NASA GRC Icing Research Tunnel

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Introduction:

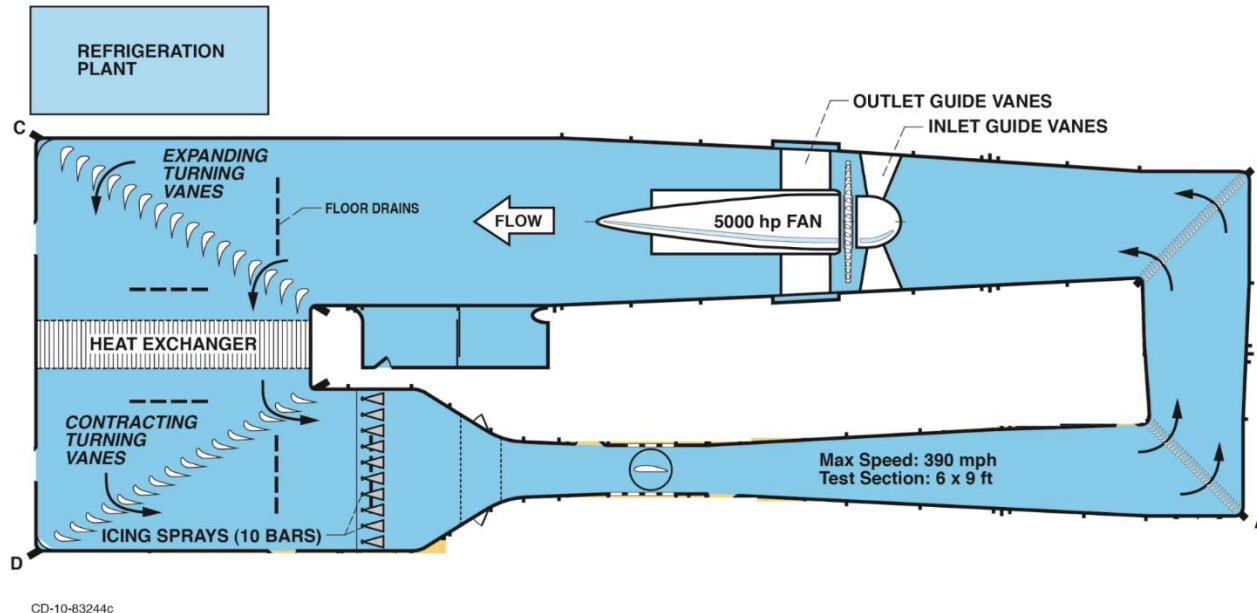
- The NASA Glenn Icing Research Tunnel (IRT) is a facility that is heavily utilized for development/certification of aircraft ice protection systems and icing research.
 - Data from the IRT has been accepted by the FAA, EASA, CAA, and JAA in support of manufacturers' icing certification programs.
- The IRT had been using an Icing Blade technique to measure cloud liquid water content since 1980.
- The IRT conducted testing with Multi-Element sensors from 2009 to 2011 to assess performance. **These tests revealed that the Multi-Element sensors showed some significant advantages over the Icing Blade.**
- Results of these and other tests are presented here.

Outline:

- Facility Description (IRT)
- Description of the Multi-Element Sensor
 - Components
 - Physics (theory of operation)
 - Processing Multi-Element data
- Description of the Blade
 - Measurement Principles
 - Ludlam Limit
- Comparisons of Multi-Element Sensor to Blade
 - Varying water content
 - Varying speed
 - Varying drop size (Large drops, SLD)
- Conclusions:
 - Strengths of Blade
 - Limitations of Blade
 - Strengths of Multi-Element
 - Limitations of Multi-Element

Test Facility

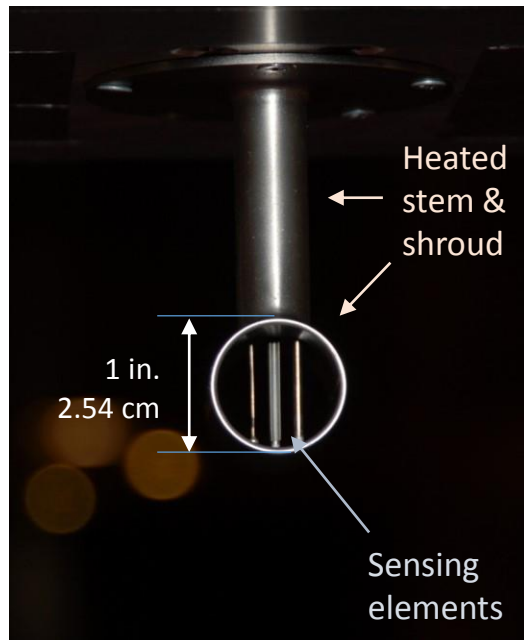
Icing Research Wind Tunnel



- **Test section size: 6 ft. x 9 ft. (1.8 m x 2.7 m)**
 - All LWC & MVD calibration measurements are made in the center of the test section
 - LWC uniformity is $\pm 10\%$ for the central 4 ft x 6 ft
- **Calibrated test section airspeed range: 50 – 325 kts**
- **Air temperature: -40 degC static to +10 degC total**
- **Calibrated MVD range: 14 – 270 μm**
- **Calibrated LWC range: 0.15 – 4.0 g/m³ (function of airspeed)**
- **Two types of spray nozzles:**
 - Standards = higher water flow rate
 - Mod1 = lower water flow rate

The Multi-Element Sensor

From Science Engineering Associates, Inc.



- Commonly known as “the Multi-Wire”
- Typical Multi-Wire shrouds contain 3 sensing elements of various sizes
 - Different element types are designed for better response to different conditions
 - Elements vary in diameter and in shape
 - IRT typically uses just the TWC element for LWC calibration
- A compensation wire is located behind central element
 - Shielded from impinging liquid/ice water
 - measures changes coming only from airspeed, air temperature, air pressure, and relative humidity

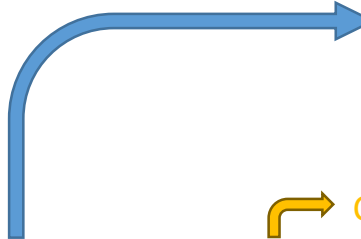



Multi-Element Sensor Theory of Operation



- A voltage is applied across each of the elements to maintain them at a temperature of 140 degC
 - Elements are cooled by convection and impinging water
- Data system records the power required to maintain each element at constant temperature.
- The compensation wire is shielded to stay dry
 - Changes in the comp wire during a spray are reflected in the calculated water content
- The recorded powers are used to calculate liquid water content:

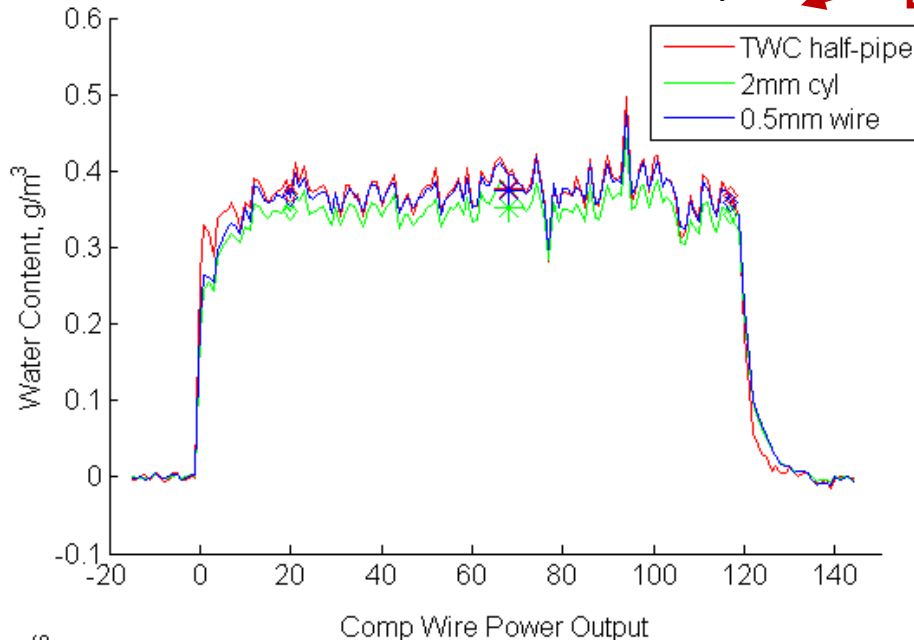
$$P_{\text{elem,wet}} = P_{\text{elem,tot}} - \underbrace{(\text{offset} + \text{slope} * P_{\text{comp,dry}})}_{\text{Subtract off cooling from dry air, correlated to comp wire}}$$

$$LWC = \frac{P_{\text{elem,wet}}(\text{watts}) * 2.389 \times 10^5}{\underbrace{\left[1.0 \frac{\text{cal}}{\text{g} * ^\circ\text{C}} (T_{\text{evap}} - T_{\text{ambient}}) + L_{\text{evap}} \frac{\text{cal}}{\text{g}} \right]}_{\text{Amount of energy required to raise the drop temp to evaporative temperature and then evaporate it (cal/g)}} * \underbrace{TAS \frac{\text{m}}{\text{s}} * l_{\text{elem}} \text{mm} * w_{\text{elem}} \text{mm}}_{\text{Sample volume of sensing element (m}^3\text{/s)}}$$

Multi-Wire Data Processing

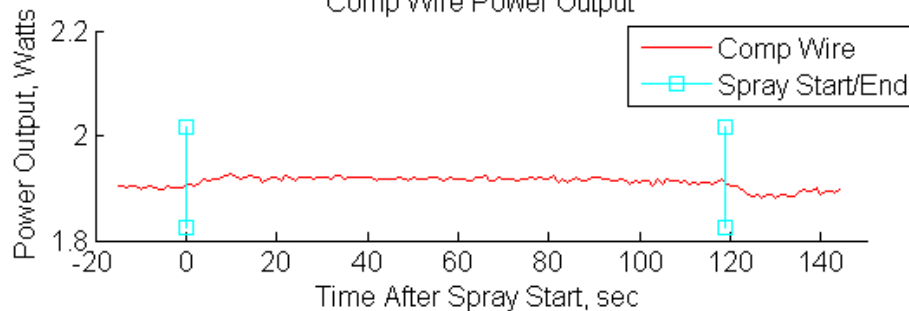
Multi-Wire Data Trace at 100 kts, 14 μ m



Multi-Wire data trace, showing all 4 sensing elements

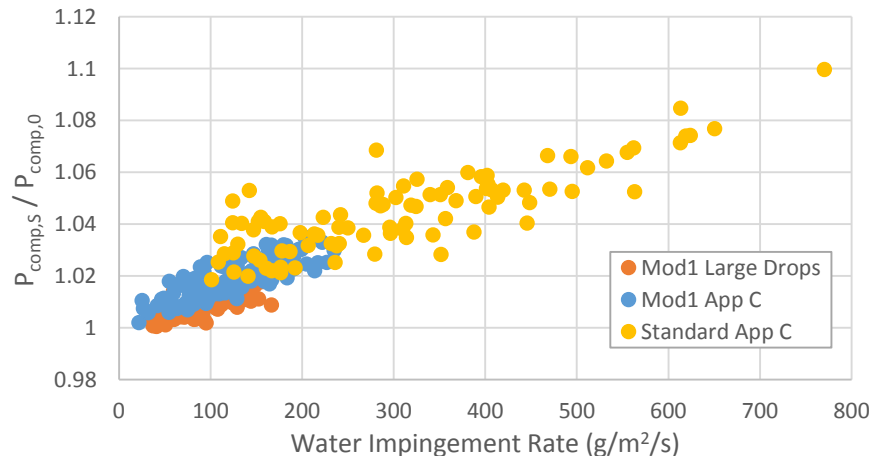
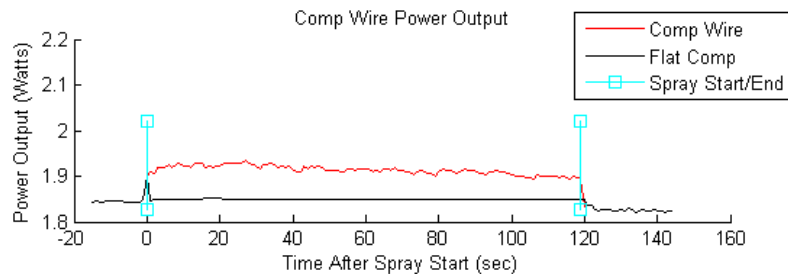
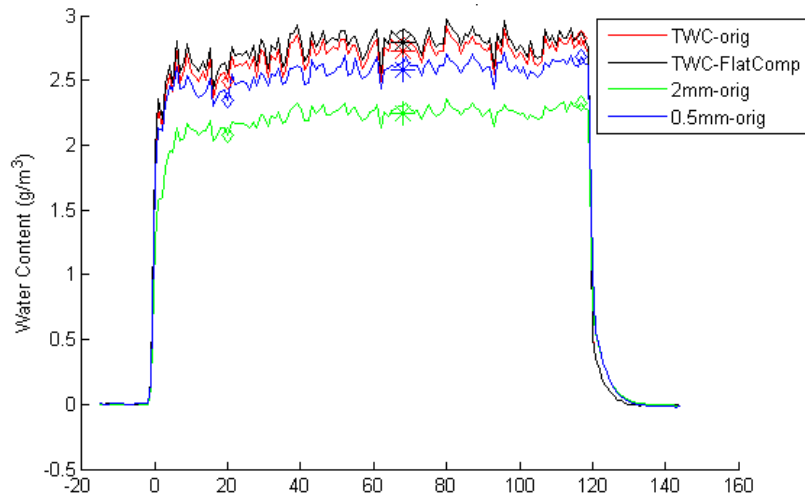
Multi-Wire Data processing:

- IRT uses only the water content values from the TWC element
 - *A comparison of the different elements is beyond the scope of this presentation*
- In-house MATLAB code averages and tares the recorded values
 - Code also flags data irregularities
- Measured TWC is corrected for **collision efficiency***
- TWC is calculated based on the *pre-spray* comp wire power

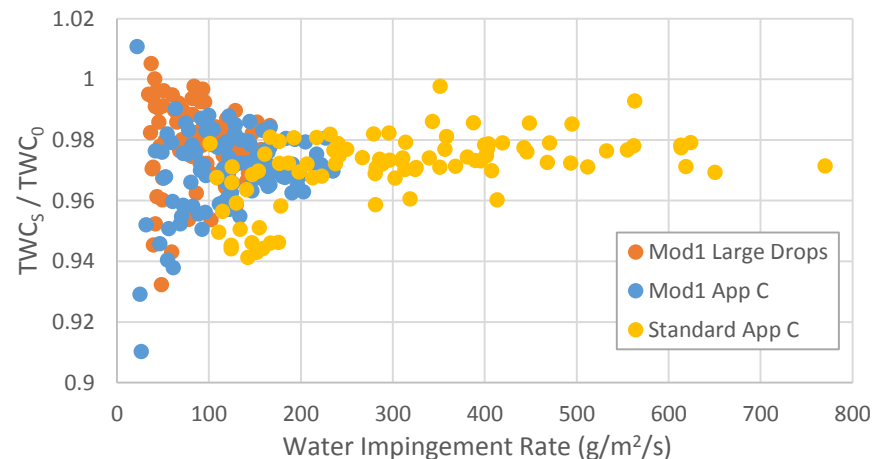


*3D collection efficiency: Rigby, D.L., Struk, P.M., and Bidwell, C., "Simulation of Fluid Flow and Collection Efficiency for an SEA Multi-Element Probe," 6th AIAA Atmospheric and Space Environments Conference, AIAA-2014-2752, 2014.

Compensation Wire Jump Correction



- The comp wire power displays a step-increase and step-decrease that coincides with spray start/end. The increase in power can be directly correlated to water impingement rate.
(Impingement Rate = $TWC \times \text{Airspeed} \times E_{tot}$)
- TWC data has been corrected by using a “flat-lined” compensation wire power: equal to the average before start of spray (0-20 sec).
- Impact on data averages to be around 2% for high impingement rates. Note that at low impingement rates, TWC values are low, so a high percentage difference may be only a few hundredths of a g/m³.



The Icing Blade



- Simple piece of stainless steel:
1/8" x 6" x 3/4"
 - 3.175 mm x 154.2 mm x 19.05 mm
- Was the standard measurement for all LWC calibrations in the IRT from 1980 to 2011
- Ice Accretion: Requires Rime Ice
 - Tunnel total air temp of -18 to -20 degC
 - Adjust spray time to collect approx. 0.15 in. (3.8 mm) of ice.
(12 ≤ t ≤ 200 sec)
 - Width of ice is measured (< 0.200 in., or 5mm) to make sure changes in collection efficiency are minimal
- 3 measurements (1 in. apart) of ice thickness—use the median value

$$LWC = \frac{1710 * d}{V * t * E_b}$$

d = ice thickness (mm)

V = tunnel airspeed (kts)

t = spray time (sec)

E_b = Collection efficiency
(calculated, function of
airspeed, air density,
& drop size)

1710 = constant—contains
unit conversions and
an assumed ice density
of 0.88

The Ludlam Limit *(for the blade)*

- **Ludlam Limit**: the supercooled water impingement rate above which not all impinging water will freeze for a given air temperature and airspeed (impingement rate above which the measured LWC is reduced)
 - Water impingement rate is a function of the airspeed, LWC, & Collection Efficiency
- Stallabrass applied Ludlam's work to derive the Ludlam limit for a 1/10th inch diam. rotating cylinder. We used his data to calculate the limit at -20 degC

Consider: We have a 1/8th in. Blade,
not a 1/10th in. rotating cylinder.

- **Collection Efficiency**:
 - We have data that shows the collection efficiency of the 1/8th inch blade is within 2% of that of the 1/10th inch cylinder
- **Temperature**: Stallabrass used static air temperature.
 - In the IRT, icing blade tests are conducted at a total temperature between -18 and -20 degC.
 - The blade temp is somewhere between static and total

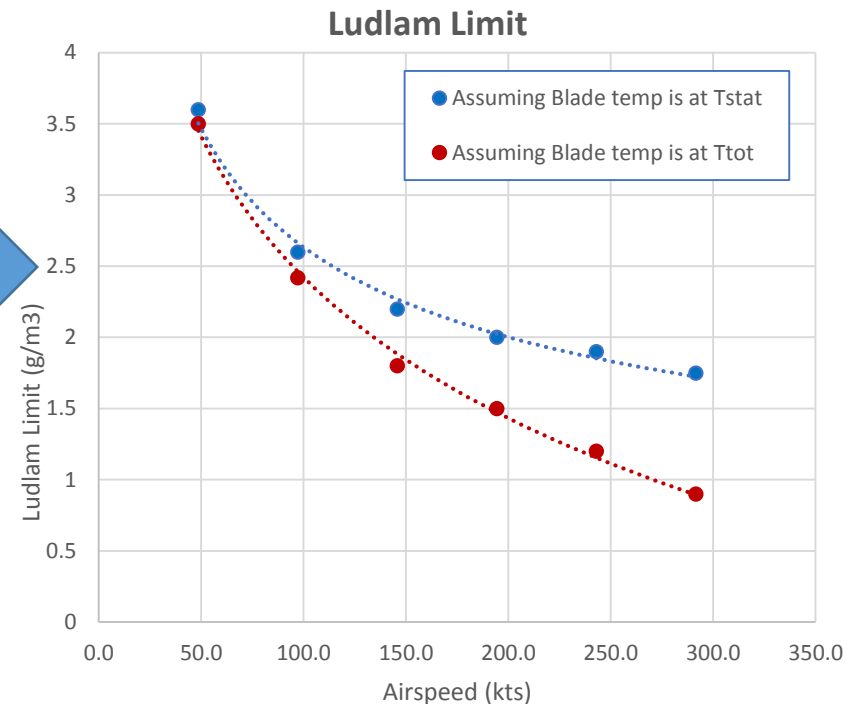


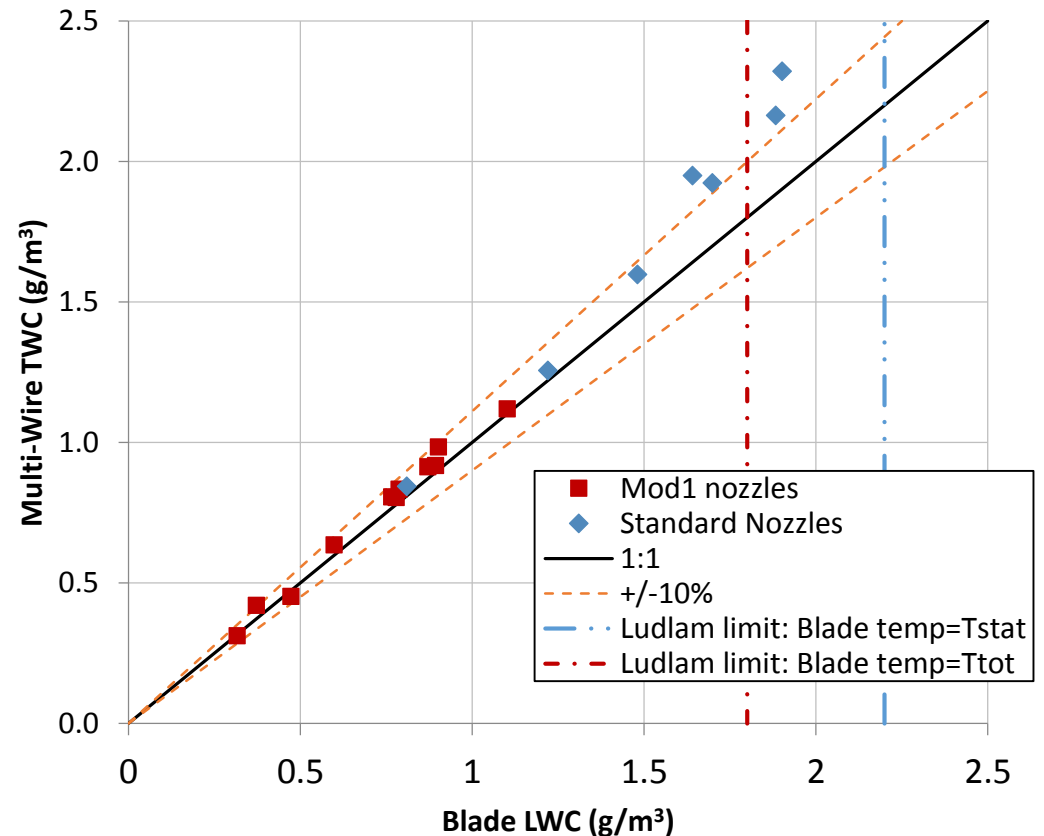
Figure: Ludlam limit as a function of airspeed for a 1/10th inch (2.49 mm) diam. cylinder and two temperature constraints [data from Stallabrass]

Comparing Multi-Wire vs. Blade

- Thorough comparison had to be done before we could switch LWC calibration instruments.
- The Multi-Wire has obvious advantages over the Blade in terms of:
 - Temperature → the Blade requires hard rime conditions
 - Test efficiency → can collect 30 conditions/day with Blade, vs. 50 conditions/day with Multi-Wire
 - Spray time → not restricted, can capture real-time trends
- We want to see how the two instruments compare, varying:
 - Liquid water content (LWC)
 - Airspeed
 - Drop size (MVD)

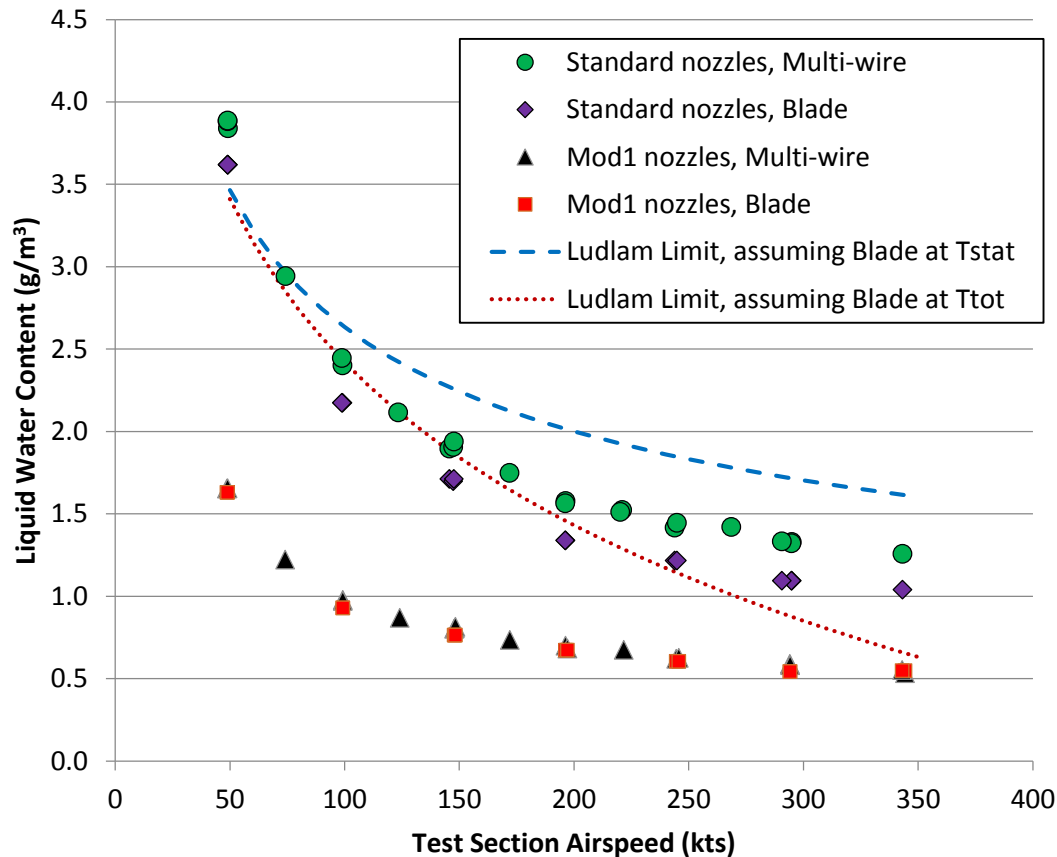
Multi-Wire vs. Blade, with respect to Liquid Water Content

- For these points:
 - Airspeed = 150 kts
 - MVD = 20 μm
 - $T_{\text{tot}} = -20 \text{ degC}$ (blade)
 - $T_{\text{tot}} = -10 \text{ degC}$ (multi-wire)
- For these conditions, the Ludlam limit is 1.8 g/m^3 if we use the total temp, and 2.2 if we use the static temp.
- This plot shows the water contents match until the LWC approaches or surpasses the Ludlam Limit



Multi-Wire vs. Blade, with respect to **Airspeed**

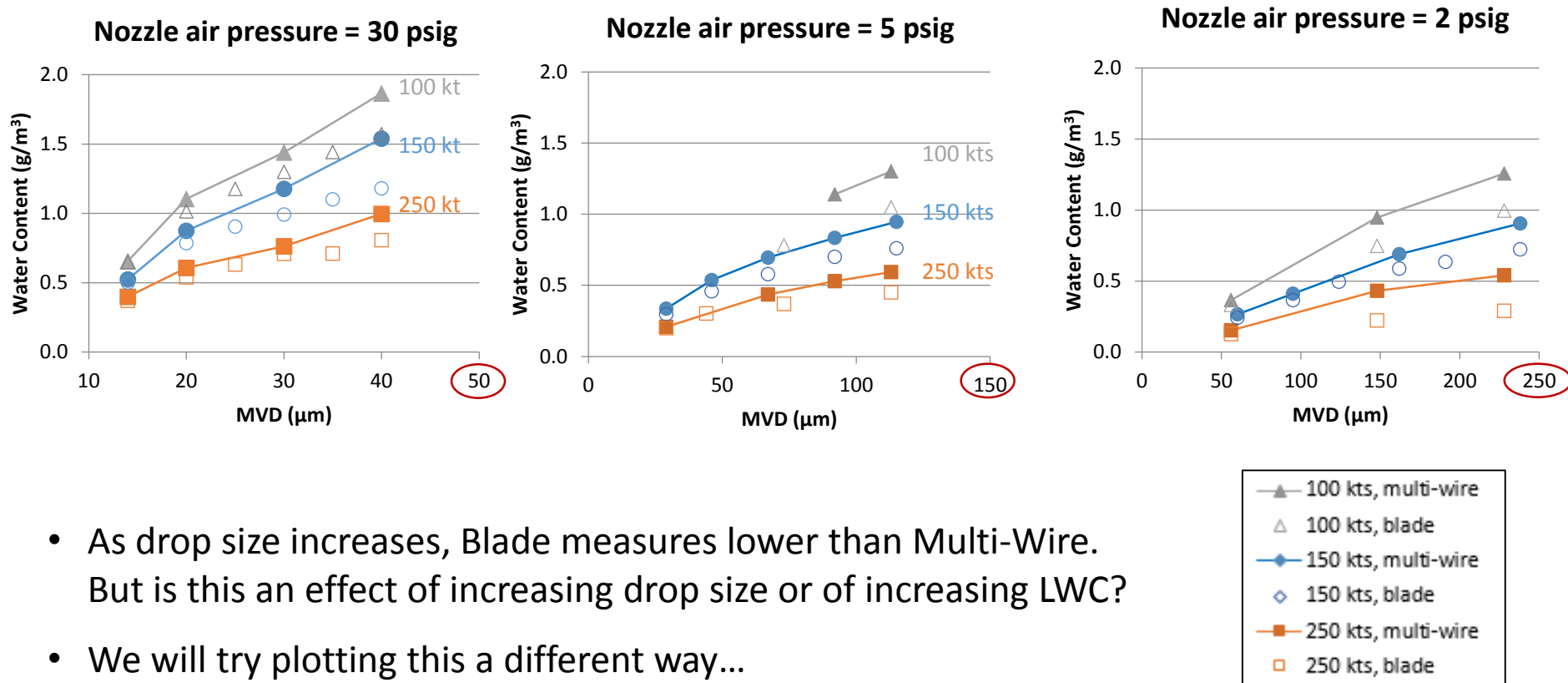
Blade & Multi-Wire LWC vs. Airspeed (MVD = 20 μm)



- Airspeed sweeps for two nozzle sets, MVD=20 μm
 - Standard nozzles are higher water flow, Blade testing requires shorter spray time.
- Plotted alongside Ludlam limit curve fit shown on previous slide
 - Limits are for Ttot = -20 degC
- The Mod1 nozzles show good agreement between the MW and the blade, even at high airspeeds
- But at higher impingement rates (LWC x airspeed x Collection Efficiency), the blade measures lower than the MW

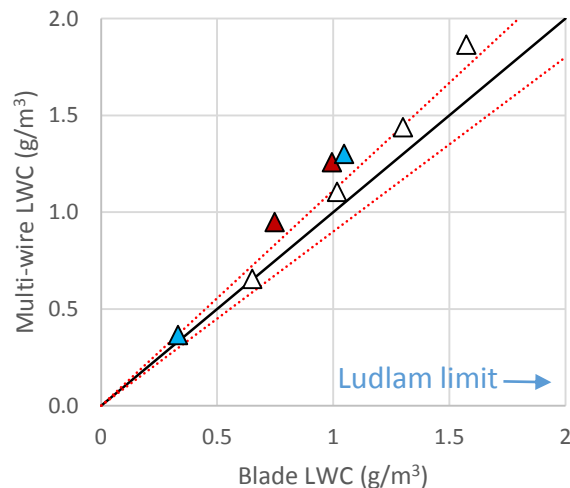
Multi-Wire vs. Blade, with respect to Drop Size (MVD)

Multi-wire vs Blade LWC, at 100, 150, and 250 kts

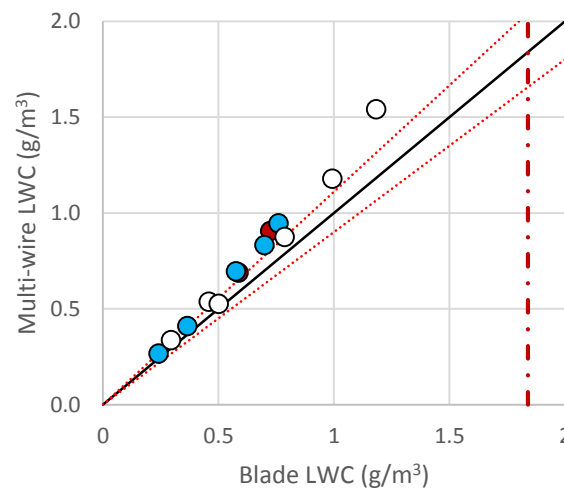


Multi-Wire vs. Blade, with respect to **Drop Size (MVD)** (part 2)

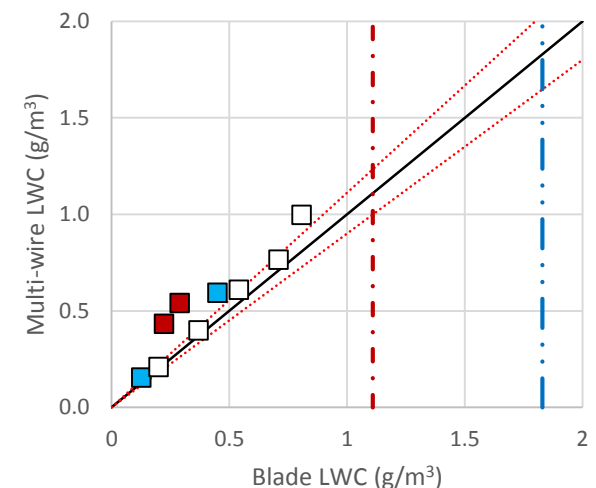
100 knots



150 knots



250 knots



MVD:

- △ 14 – 50 μm
- ▲ 50 – 125 μm
- ▲ 125 – 250 μm

- For smaller drop sizes at all velocities, there is an LWC limit at which the Blade measures lower than the Multi-Wire, even for MVD's below 50 μm.
- For larger drop sizes, the Ludlam limit can no longer account for the roll-off we see from the Blade. We suspect that we have an added problem due to mass-loss (splashing?) at larger drop sizes.

Conclusions:

Strengths of Blade

- Simplicity
- Reliability
- Researcher can see the physical ice characteristics

Limitations of Blade

- Does not respond well at higher impingement rates (Ludlam limit)
- Does not respond well at larger drop sizes (suspect mass-loss)

*Repeatability of the Multi-Wire in the IRT:
2 test conditions, repeated 27 & 29 times
over 5 test entries spanning 2 years:
Standard deviation was 2.55% and 2.25%
of the mean values*

Strengths of Multi-Wire

- Compares well to Blade for most Appendix C conditions
 - $MVD \leq 30 \mu m$
 - Moderate impingement rates
 - Some MW results validated by icing scaling tests in the IRT
- Temperature independent (data not included)
- Test efficiency
- Spray time independent
- Ability to measure ice crystals (*not addressed in this presentation*)

Limitations of the Multi-Wire

- No limitations of the multi-wire were found from these tests

Questions?

