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

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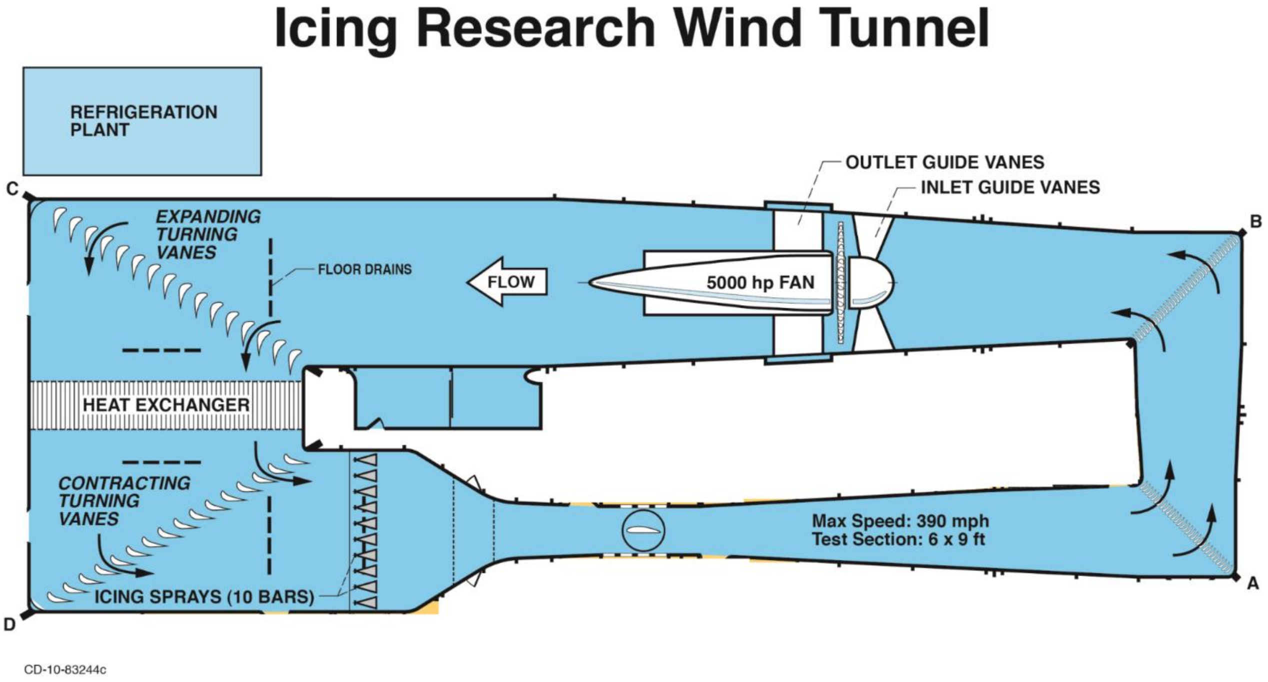
Introduction:

- 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

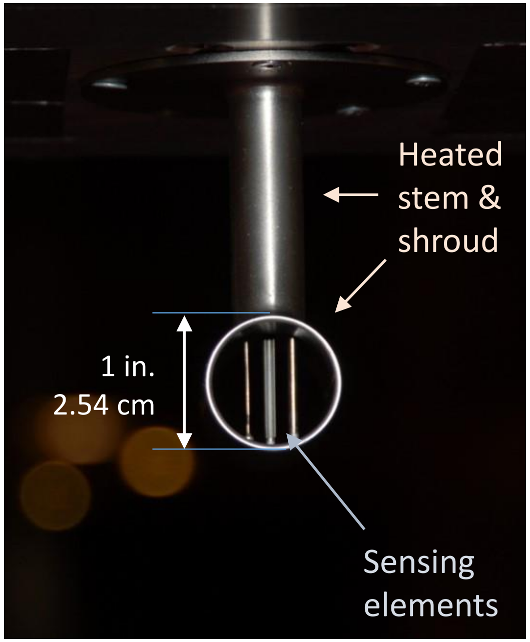
Test Facility



- **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 ±10% for the central 4 ft x 6ft
- **Calibrated test section airspeed range: 50 – 325 kts**
- **Air temperature: -40 degC static to +20 degC total**
- **Calibrated MVD range: 14 – 270 µm**
- **Calibrated LWC range: 0.15 – 4.0 g/m^3 (function of airspeed)**
- **Two types of spray nozzles:**
  - Standards = higher flow rate
  - Mod1 = lower 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:

$$P_{elem,wet} = P_{elem,tot} - \underbrace{(offset + slope * P_{comp,dry})}$$

Subtract off cooling from dry air, correlated to comp wire

Conversion factor

$$LWC = \frac{P_{elem,wet}(watts) * 2.389 \times 10^{5}}{\underbrace{\left[L_{evap}\frac{cal}{g} + 1.0\frac{cal}{g * {}^{0}C}\left(T_{evap} - T_{ambient}\right)\right]} * \underbrace{TAS\frac{m}{s} * l_{elem}mm * w_{elem}mm}}$$

Amount of energy required to raise the drop temp to evaporative temperature and then evaporate it (cal/g)

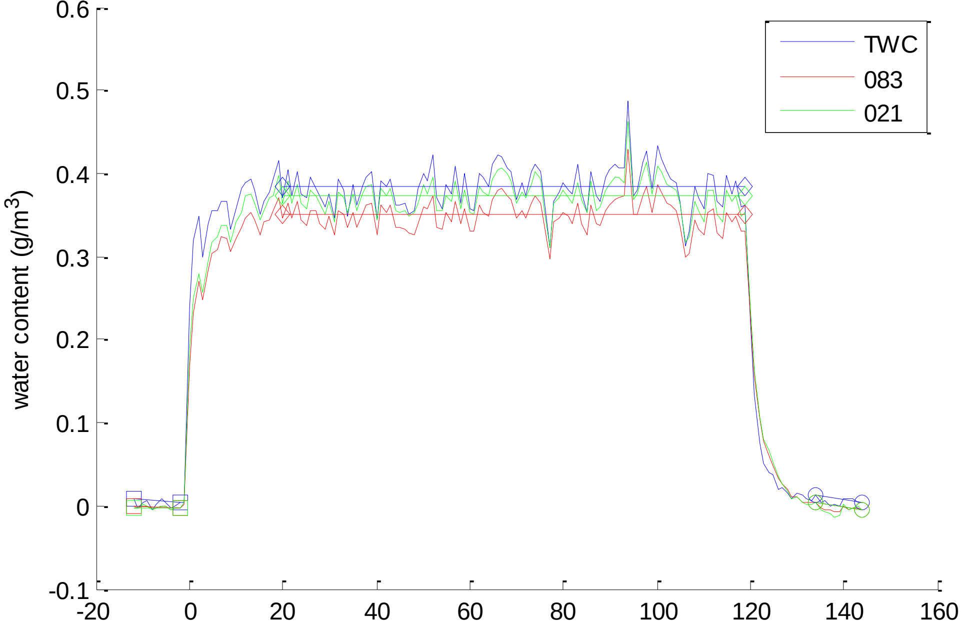
Sample volume of sensing element (m^3/s)

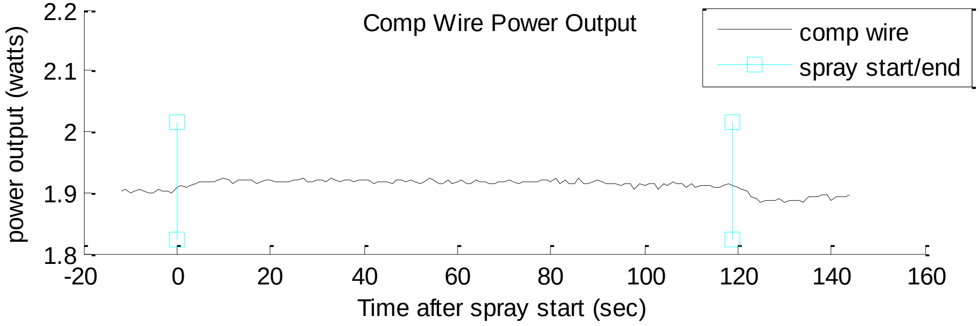
Source: the SEA User's Manual

Multi-Wire Data Processing

Multi-Wire data trace, showing all 4 sensing elements

Multi-Wire Data Trace at 100 kts, 14 µm



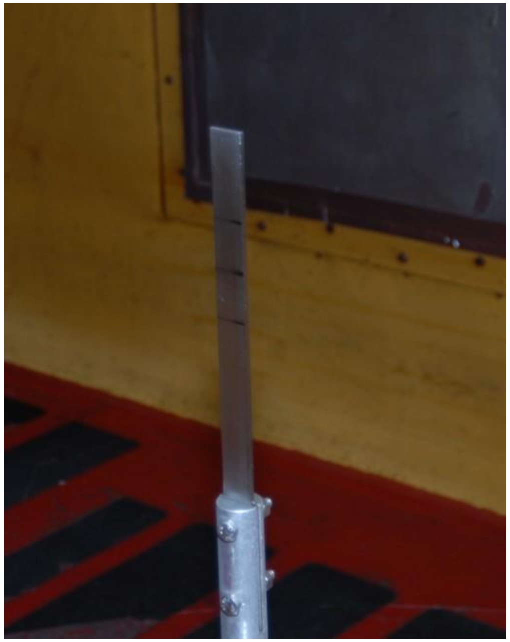


Multi-Wire Data processing:

- 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 collection efficiency*

**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.*

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)—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

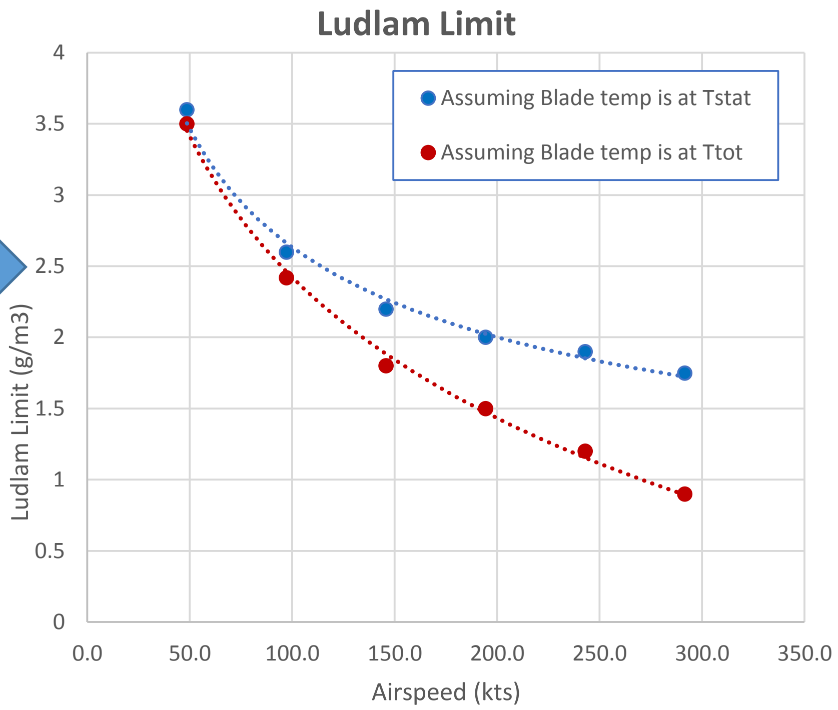


Figure: Ludlam limit as a function of airspeed for a 1/10th inch (2.49 mm) diam. cylinder and two temperature constraints [data from Stallabrass]

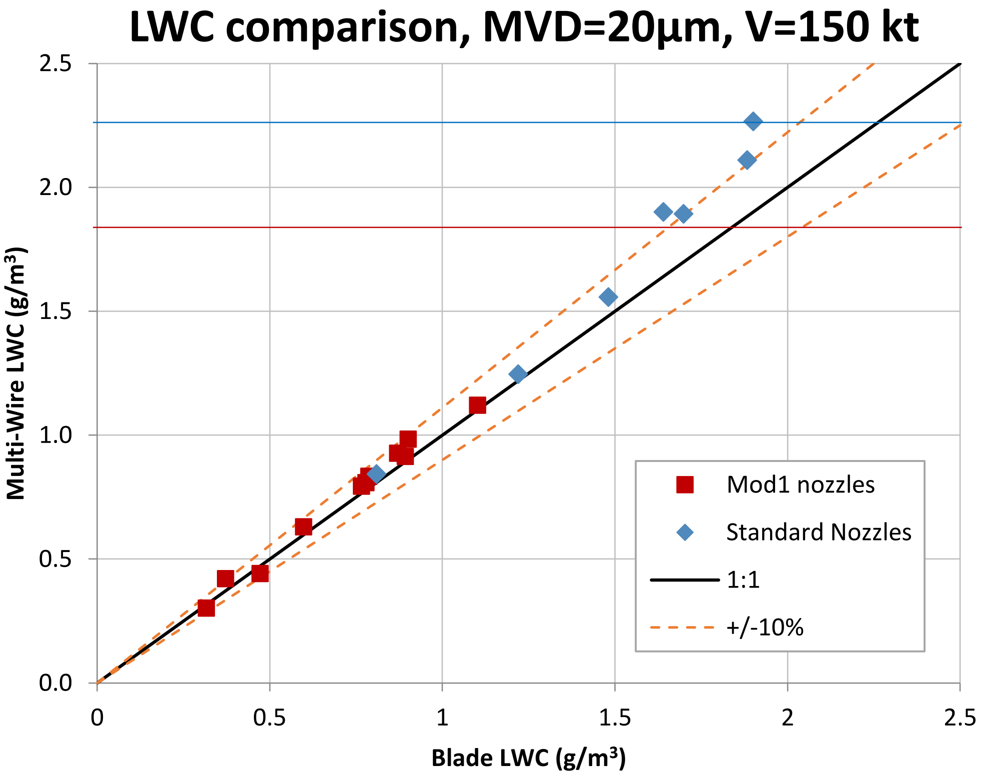
Stallabrass, J. R., "An Appraisal of the Single Rotating Cylinder Method of Liquid Water Content Measurement," National Research Council Canada Internal Report, LTR-LT-92, 1978.

Comparing Multi-Wire vs. Blade

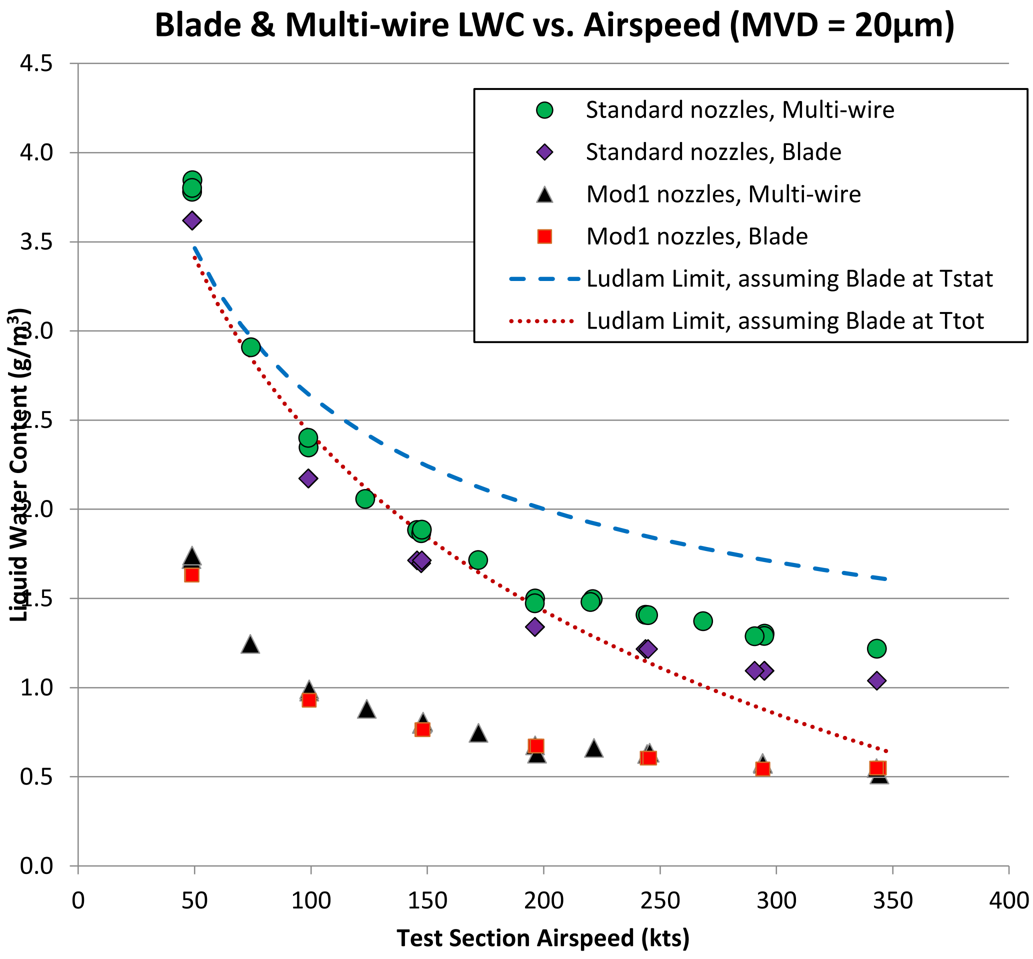
- Thorough comparison had to be done before we could switch LWC calibration instruments.
- The Multi-Wire has obvious advantages over the Blade in terms of:
  - Temperature → the Blade requires hard rime conditions
  - Test efficiency → can collect 30 conditions/day with Blade, vs. 50 conditions/day 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_{tot} = -20 degC (blade)
  - T_{tot} = -10 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



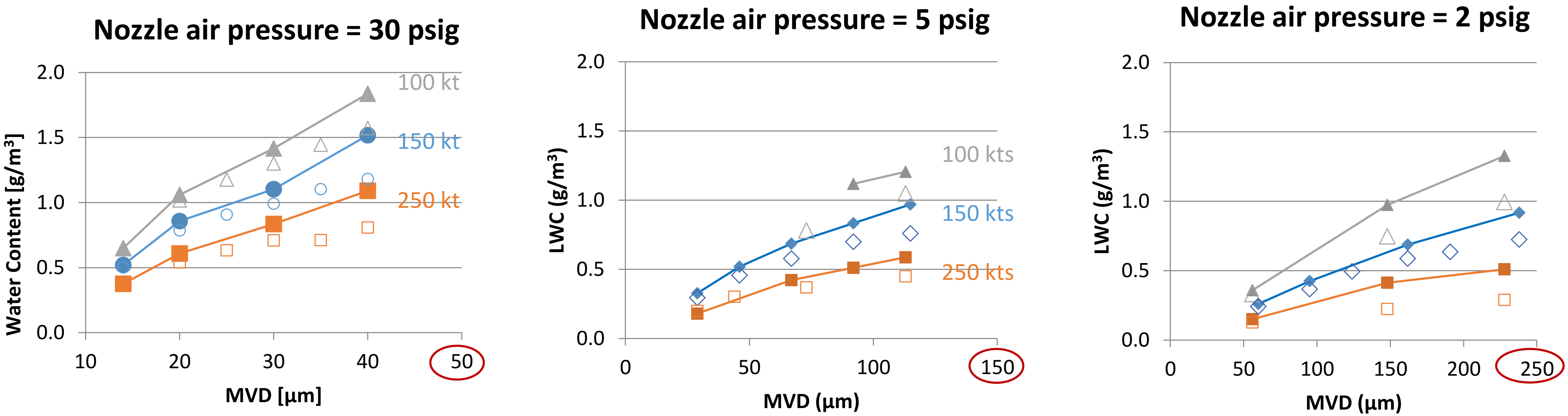
Multi-Wire vs. Blade, with respect to **Airspeed**

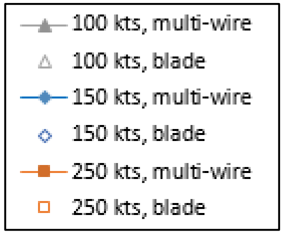


- Airspeed sweeps for two nozzle sets, MVD=20µm
  - Standard nozzles are higher water flow, Blade testing requires shorter spray time.
- Plotted alongside Ludlam limit curve fit shown on previous slide
  - Limit for a temperature of -20 degC
- The Mod1 nozzles show good agreement between the MW and the 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)**

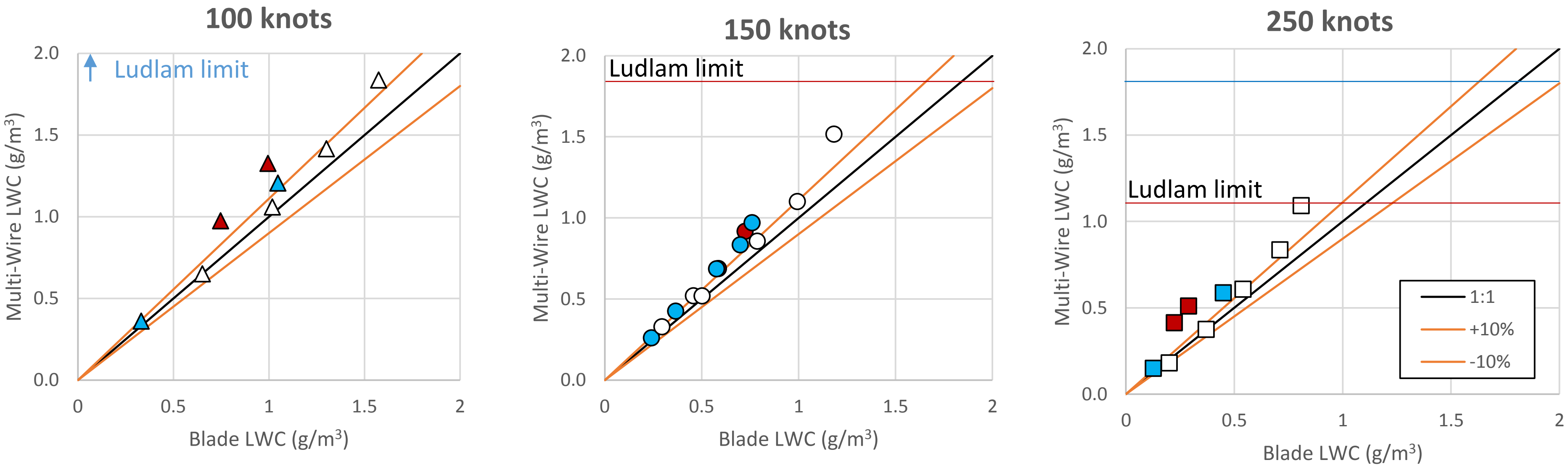
Multi-wire vs Blade LWC, at 100, 150, and 250 kts





- As drop size increases, Blade measures lower than Multi-Wire. But is this an effect of increasing drop size or of increasing LWC?
- We will try plotting this a different way…

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



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)

Strengths of Multi-Wire

- Compares well to Blade for most Appendix C conditions
  - MVD ≤ 30 μm
  - Moderate impingement rates
  - Some MW results validated by icing scaling tests in the IRT
- Temperature independent
- 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?

HX5 SIERRA
JOINT VENTURE

NASA