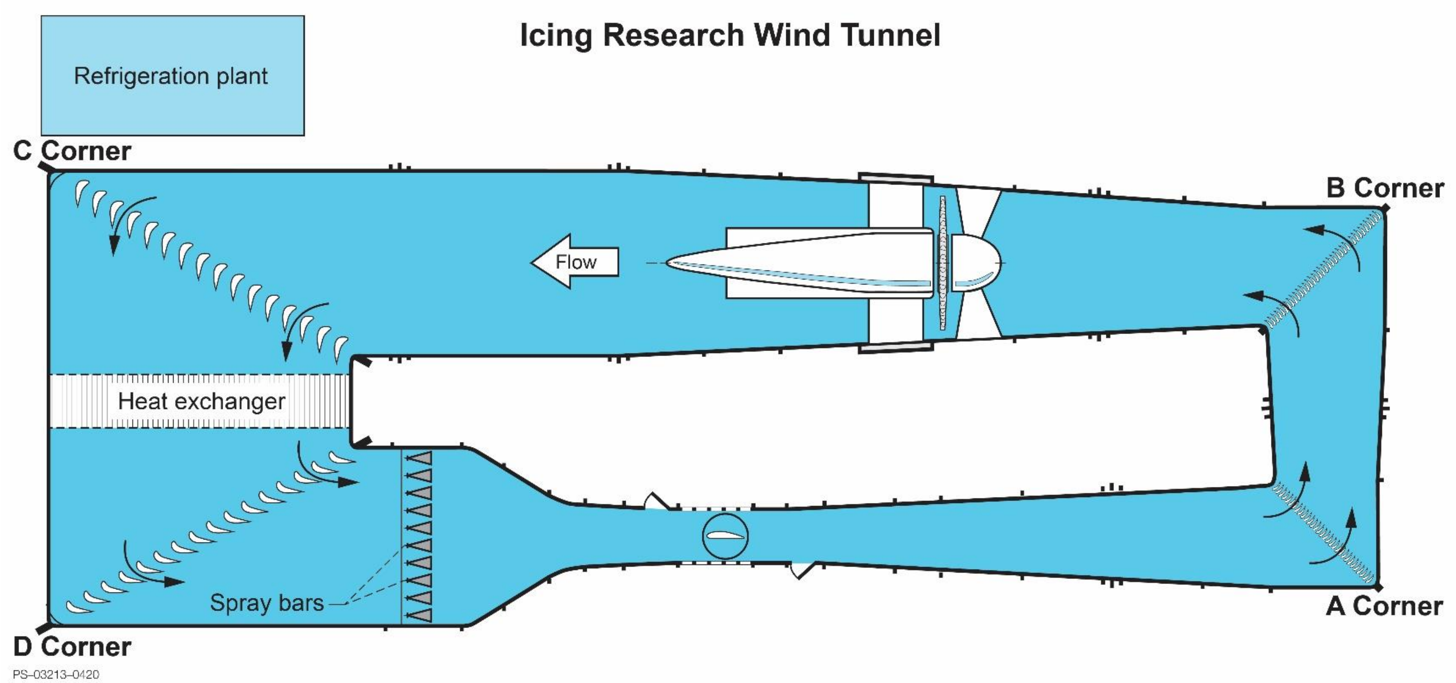
NASA Glenn Icing Facilities Advancements

Presented by:

Emily Timko (Amentum)

Icing Research Tunnel (IRT)



- Test section size: 6 ft. x 9 ft. (1.8 m x 2.7 m)
- LWC & MVD calibration measurements are made in the center of the test section
- LWC uniformity: ±10% for central 4 ft x 6 ft
- Calibrated test section airspeed: 50 –300 kts
- Air temperature: -40ºC static to +10ºC total
- Calibrated MVD range: 14 –300 µm
- Calibrated LWC range: 0.19 –4.5 g/m^3 (function of airspeed)
- Two types of spray nozzles:
  - Standards = higher water flow rate
  - Mod1 = lower water flow rate

Cloud Calibrations

- Calibration schedule
  - SAE's ARP-5905, "Calibration and Acceptance of Icing Wind Tunnels"
    - Full calibration every 5 years OR following a change to facility
      - Uniformity, drop size, water content
    - Interim calibration one year after full calibration
      - Uniformity, drop size, and water content
    - Check calibrations every 6 months after full calibration
      - Uniformity and water content

2024:
January
Full Calibration Completed

2024:
September
Check Calibration Performed after Maintenance Shutdown

2025:
January
Interim Calibration Completed

2025:
May
Check Calibration Performed

2025:
September
Check Calibration Performed after Maintenance Shutdown

2026:
January
Check Calibration Performed

Cloud Calibrations

- Calibration specs/tolerances
  - ARP-5905, Table 1
- IRT Performance
  - Appendix C
    - +/- 10% for both LWC and MVD
  - Large Drop (MVD >50µm)
    - +/-20% for both LWC and MVD

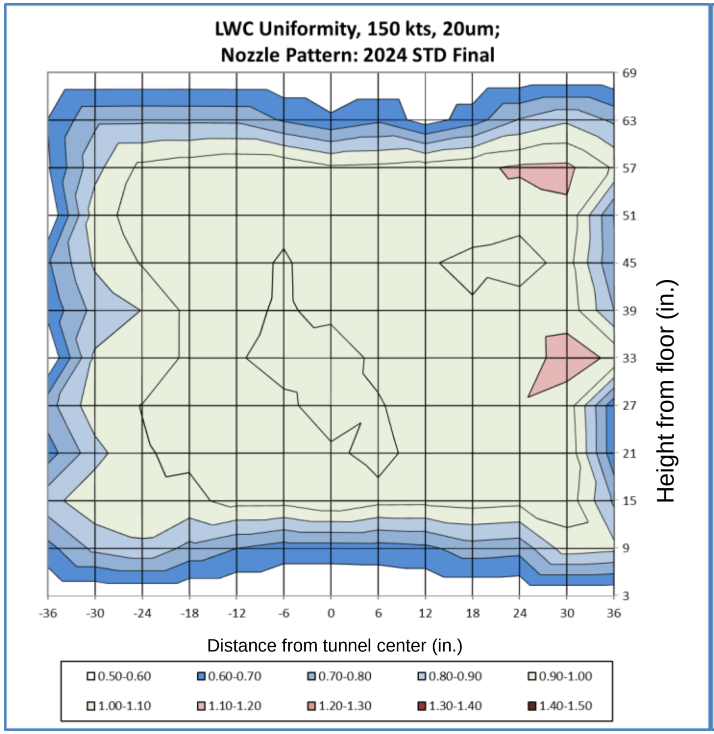
	Measurement Instrumentation Maximum Uncertainty	Tunnel Centerline Temporal Stability[2]	Spatial Uniformity[3]	Limit Value[4]	Test Section Calibrations (see Section 7)[5]
Aerothermodynamic Parameters					
True Airspeed[6][7]	±1%	±2%	±2%	N/A	±1%
Total Air Temperature below -30 °C[8]	±2 °C	±2 °C	±2 °C	N/A	±2 °C
Total Air Temperature Between -30 and +5 °C[8]	±0.5 °C	±0.5 °C	±1 °C	N/A	±0.5 °C
Flow Angularity	±1.0°	N/A	±2°	±3°	N/A
Pressure Altitude	±50 m	±50 m	N/A	N/A	±50 m
Flow Turbulence					
(P_a-Off or minimum)[9]	±0.25%	N/A	<2%	2%[11]	N/A
(P_a-On at maximum)[10]	±0.25%	N/A	<2%	5%[11]	N/A
Cloud Parameters					
Liquid Water Content[12]	±10%	±20%	±20%	N/A	±10%
Median Volume Diameter[13]	±20%	±10%[14]	N/A	N/A	±20%
Relative Humidity	±3%	N/A	N/A	N/A	[15]

From: ARP5905 "*Calibration and Acceptance of Icing Wind Tunnels*" SAE International, page 13

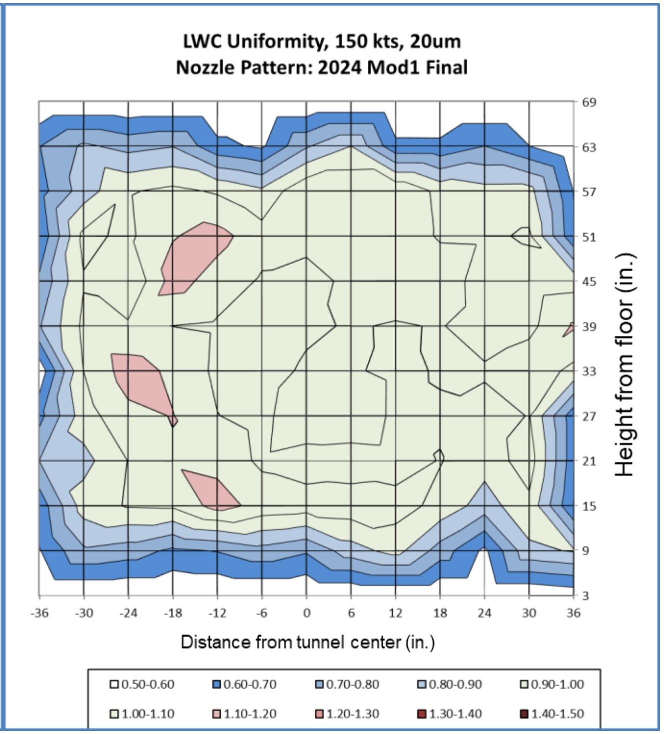
Cloud Uniformity

- Measured with a 6 ft. x 6 ft. grid (1.83m x 1.83m)
  - Grid extends floor to ceiling
  - Mesh elements are spaced every 6 in (15.24 cm).
  - Measurements made on vertical elements at 6-inch intervals, starting 3 inches from the tunnel ceiling
- Digital calipers used to measure ice thickness accreted at center mesh points of vertical elements
- Uniformity is established by turning nozzles on & off and iterating measurements until a uniform map is established
- Values are plotted as a ratio of the average of the center-12 points

Cloud Uniformity



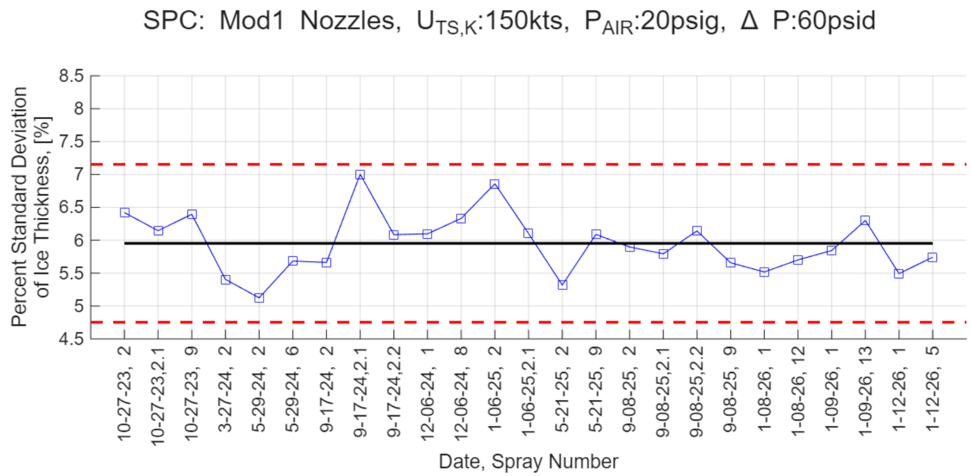
Standard Nozzles

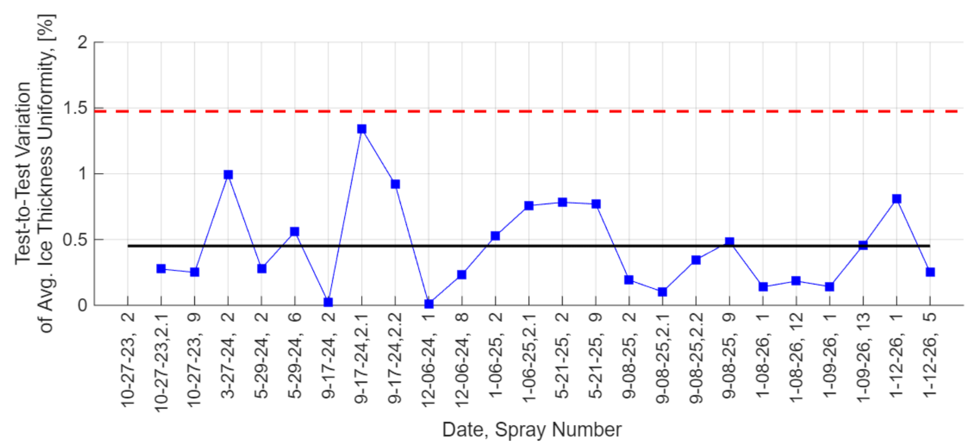


Mod1 Nozzles

Cloud Uniformity Analysis Advancement

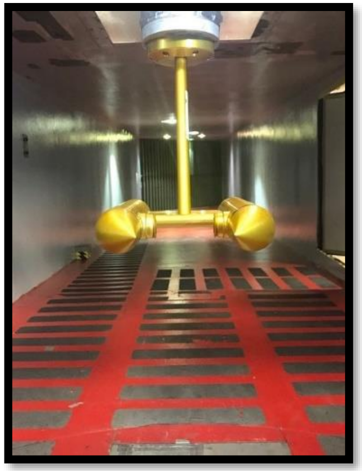
- Implementing SPC (Statistical Process Control) Charts for stability analysis
- Each map is split into zones
  - One important zone is the vertical center area where models are typically mounted
  - Other zones are outer boundary areas, central 12, expanded vertical center, etc
- Can use these graphics to assess variability and how the cloud responds with respect to different statistics and different time references
- Upper and lower control limits of +/- 3σ





**Charts show stats of the core 30

Drop Size Calibration



CDP: 2 to 50 µm

OAP-230X: 15 to 450 µm

OAP-230Y: 50 to 1500 µm

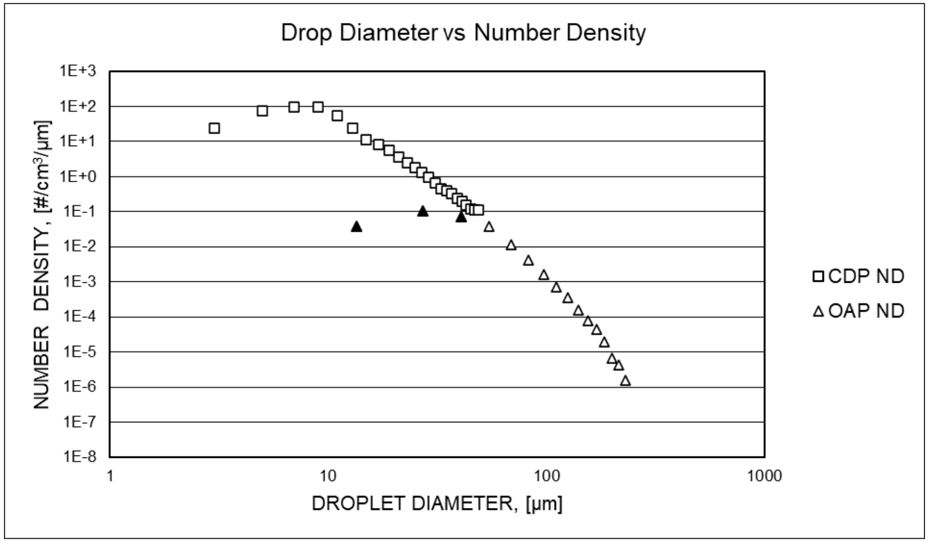
Drop Size Calibration

- Drop size distributions from the CDP are combined with the OAP-230X and OAP-230Y, for large drop conditions, to calculate Median Volumetric Diameter (MVD)
  - CDP to OAP230X crossover at 46µm
  - OAP-230X to OAP 230Y crossover at 362µm

- This Calibration = Improved understanding of probes
  - CDP: capability to map the probe's beam and determine the sample area size
    - first in 2017, now done before each calibration
    - *King-Steen, L.E., et al. "NASA Glenn Icing Research Tunnel: 2018 Change in Drop-Sizing Equations Due to Change in Cloud Droplet Probe Sample Area"*
  - Optical Array Probes: ability to measure depth of field
    - Up until now, was from Operators Manual from manufacturer and other applied corrections
    - Traverse a spinning disk to map out area of best focus

Example Drop Size Data

- Spray Setting P_{air} = 20 psig, ΔP = 60 psid
- MVD: 21.5 μm



Example Drop Size Distribution

- Spray Setting P_{air} = 20 psig, ΔP = 60 psid
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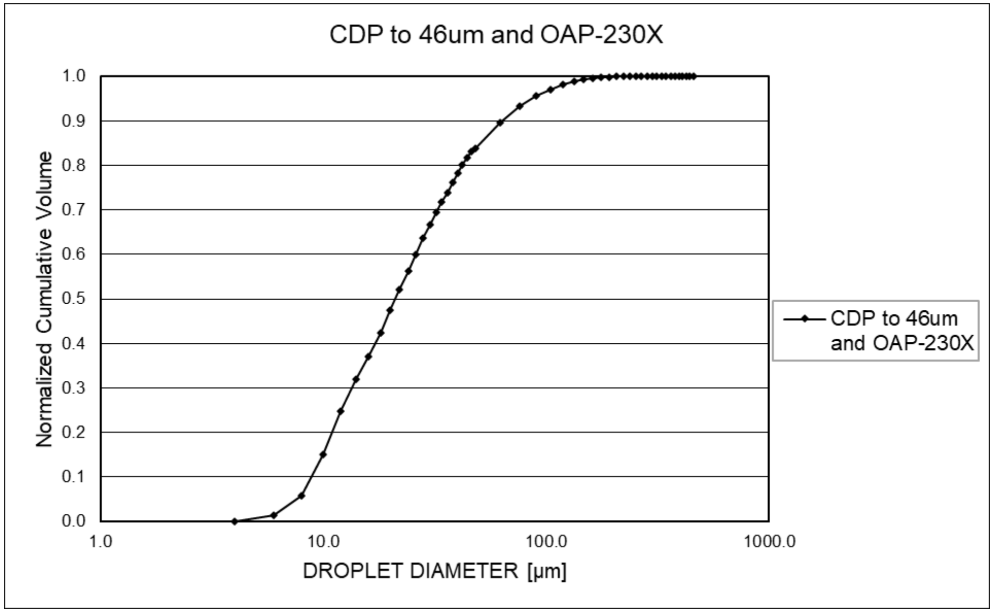
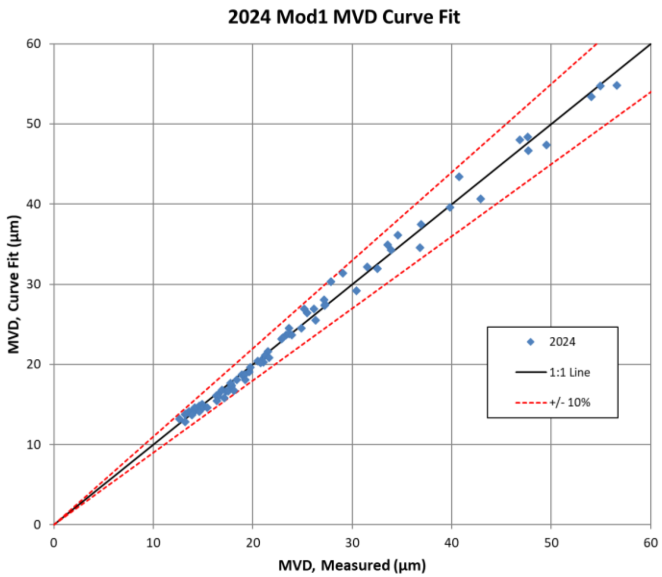
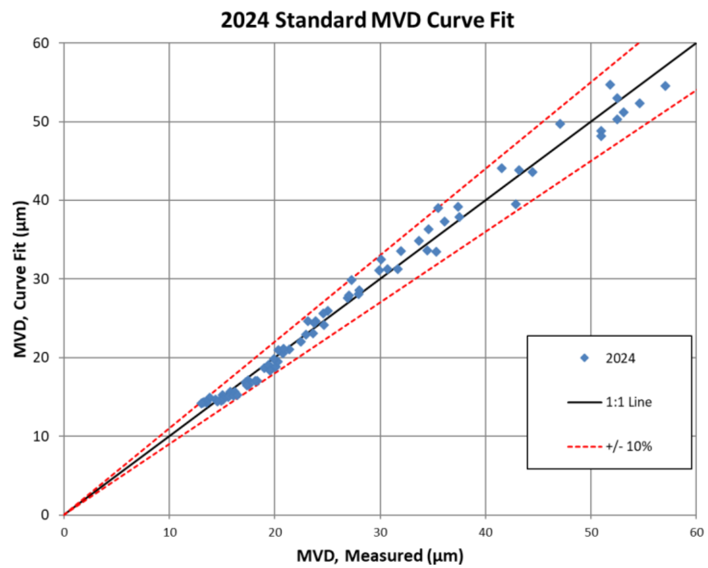


Drop-Size 1:1 Measured-vs-Curve Fit Calculation





- MVD = f(P_{air}, ΔP)
- Curve fits for Standard nozzles and Mod1 nozzles agree with measured MVD to within +/- 10%

Drop Size Probe Comparison Tests

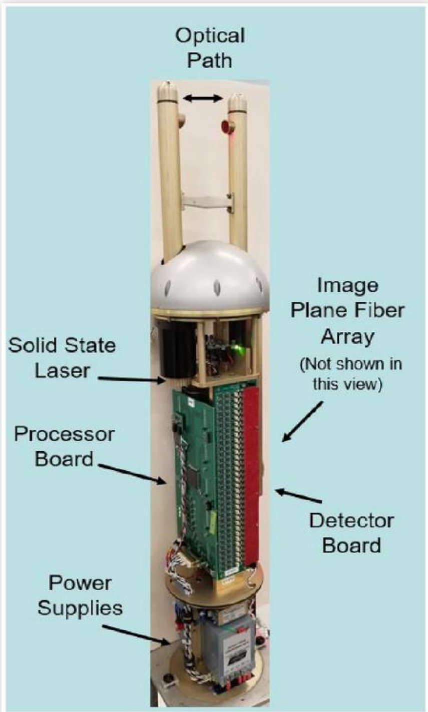
OAP-230X: 15 to 450 µm
OAP-1D2DX: 15 to 960 µm

OAP-230Y: 50 to 1500 µm
OAP-1D2DY: 50 to 3200 µm

Goal: Implementation of OAP-1D2D probes for next full calibration

Old vs New Internal Electronics

OAP-1D2DX



- 64 photodiode array
- uses fiber optics linked to avalanche photodiodes

- User-selectable feature that allows hardware rejection of recording of particles

- Particle imagery can be either the 50% or 75% shadow level

- 1D- and 2D-data streams

OAP-230Y

- 32 individual diode cards with individual wiring to diode array board

- At least one diode must be shadowed by 66% for the particle to be counted and cannot be changed by the user

- 1D data stream only

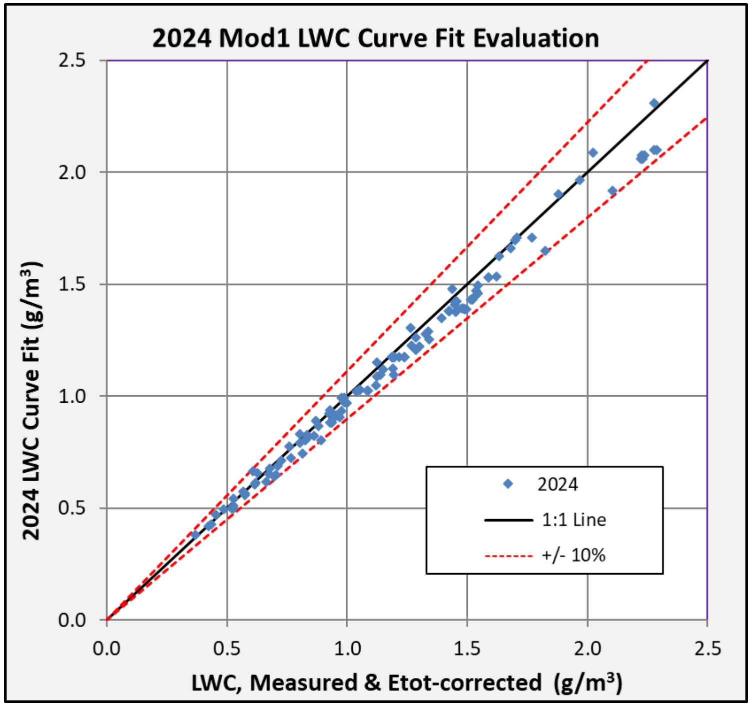
Source: Lilie, L., Bouley, D., Sivo, C., Esposito, B. et al., “A New 1D2D Optical Array Particle Imaging Probe for Airborne and Ground Simulation Cloud Measurements,” SAE Technical Paper 2023-01-1415, 2023, doi:10.4271/2023-01-1415.

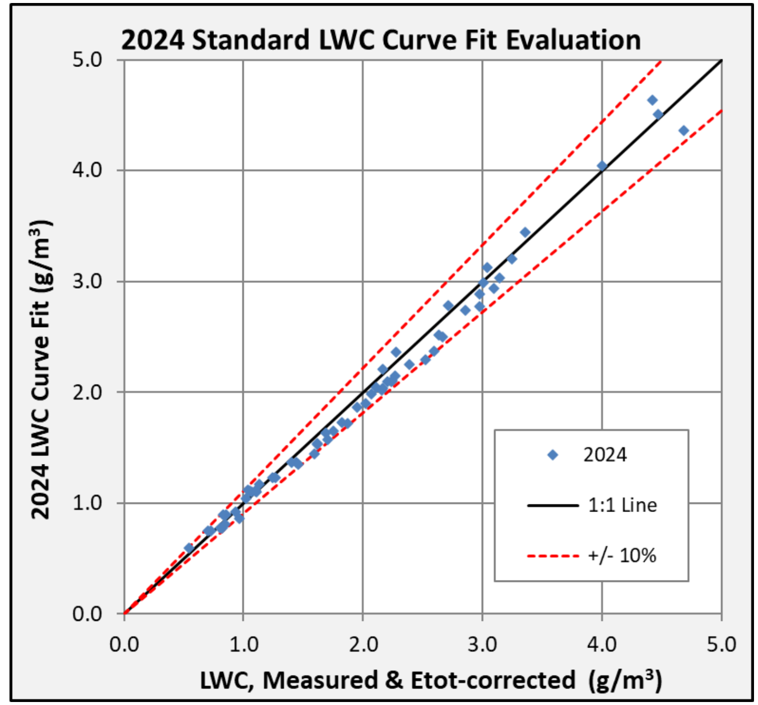
Liquid Water Content (LWC): Instrumentation

- Multi-Element Sensor ("Multi-Wire")
  - Science Engineering Associates, Inc.
  - 3 sensing elements of different size, designed for response of varying conditions
    - IRT uses the TWC element for LWC calibration

- Icing Blade
  - Stainless Steel
  - 1/8" x 6" x 3/4"
    - 3.175mm x 154.2mm x 19.05mm
  - Was the standard LWC measurement for IRT from 1980-2011
  - Still used as "sanity check" to confirm accuracy of MW

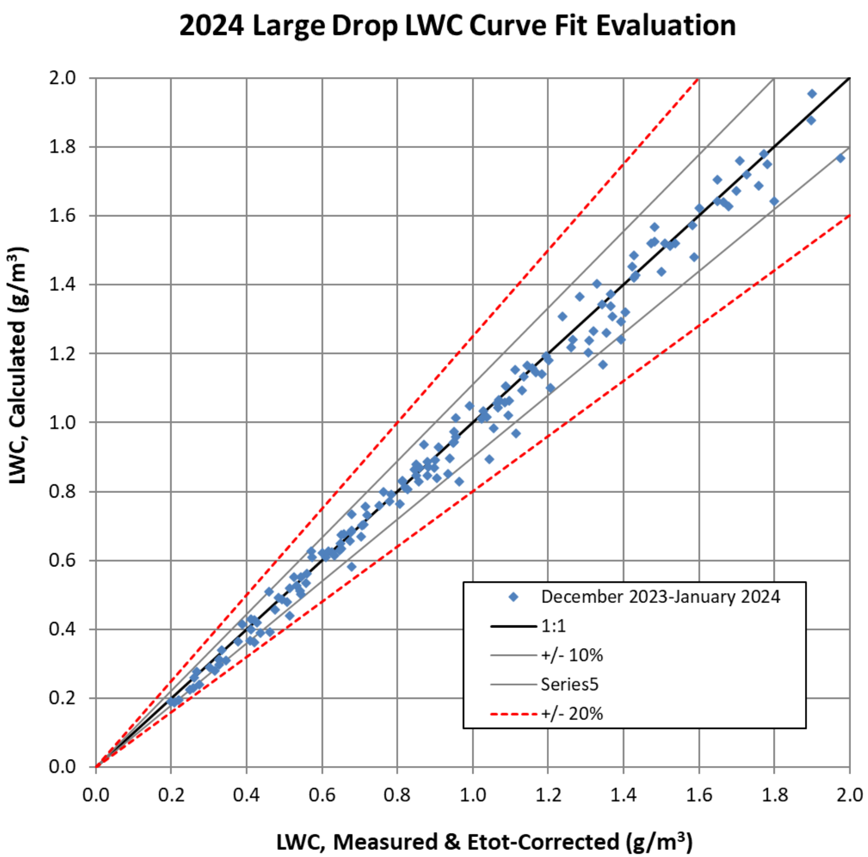
LWC 1:1 Measured-vs-Curve Fit Calculation





- LWC = f(velocity, P_{air}, ΔP, MVD)
- Curve fits for Standard and Mod1 nozzle conditions agree with measured LWC to within +/- 10%

LWC 1:1 Measured-vs-Curve Fit Calculation (LD)



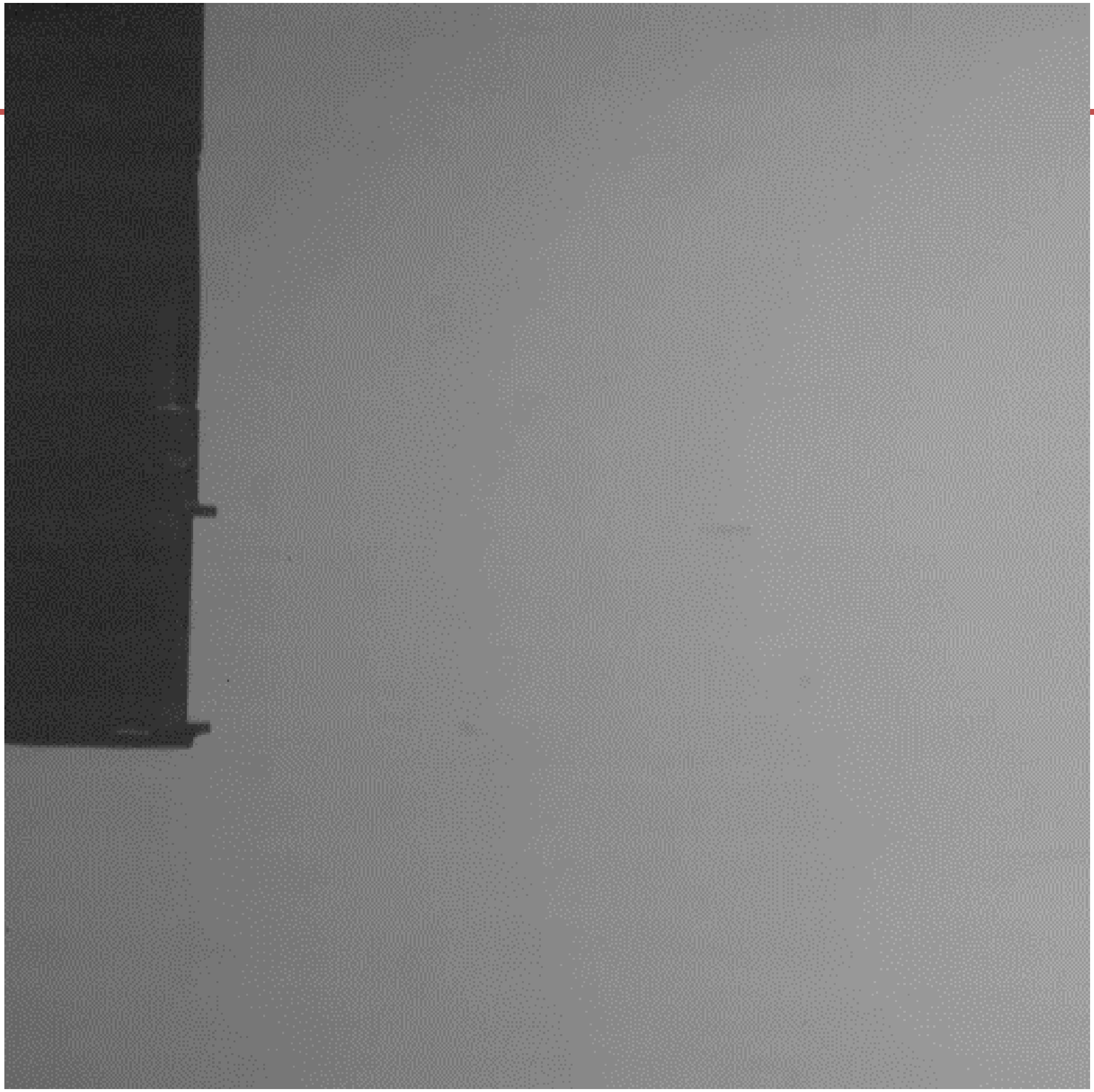
- LWC = f(velocity, P_{air}, ΔP, MVD)
- Curve fits for large drop conditions agree with measured LWC to within +/- 20%

Multi-Wire and Isokinetic Probe Comparison Tests

- IKP-vs-MW performance MW in the large drop regime

- Began some tests
  - high-speed imagery shows evidence of splashing on the TWC element at a certain size and larger
  - supports the thoughts many have had about splashing
    - Either losing mass or double-measuring what has splashed

- For the next full calibration: implement the IKP, in addition to the MW (and the sanity check of the blade) for certain spray conditions to enhance the confidence of measurement in these regimes



Video courtesy of
Ru-Ching Chen

Lower Water Content Cloud

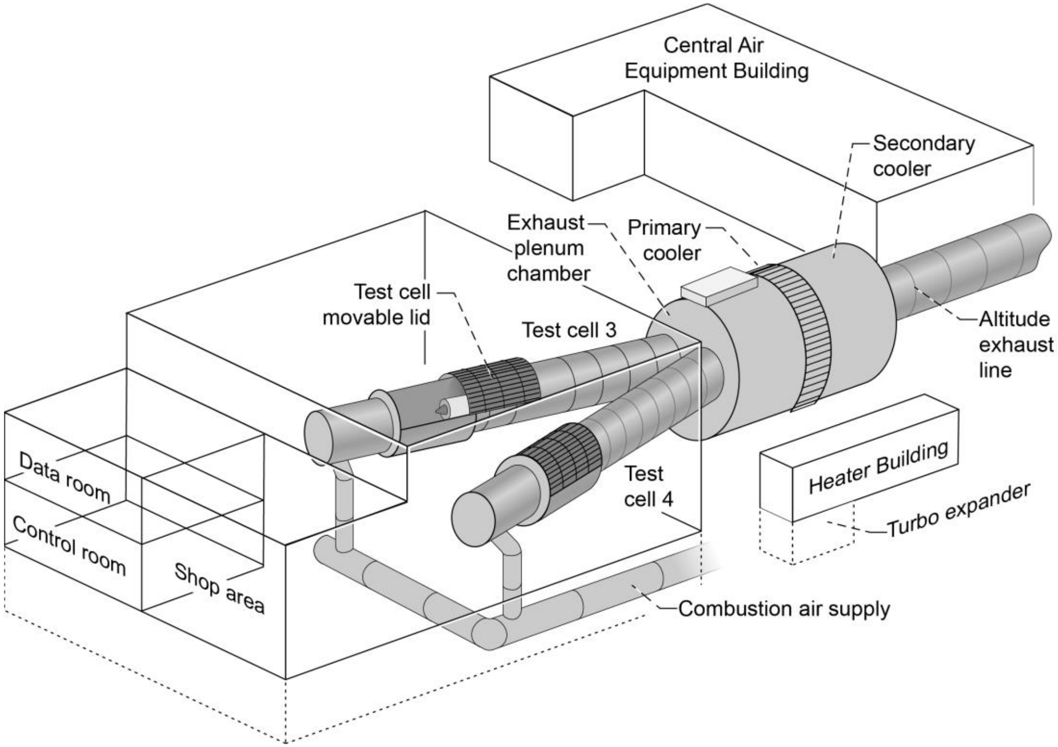
- Mod2 nozzles
  - Lower flow rate than Mod1
    - Average coefficient of flow of Mod1 = 0.0045
    - Mod2 = 0.0015
- Developed uniformity with 89 spraying nozzles
  - Mod1 cloud has 101 spraying nozzles
- Measured drop size and water content and developed preliminary curve fits
  - Appendix C – high confidence in development
  - Started on large drops (MVD > 50μm)
    - Need to collect more data for further conclusions
    - Appendix C initial results show an average reduction in water content of 65%
  - Performed ice shape tests
    - Compared overlapping Mod1 and Mod2 spray conditions
    - Compared scaled Mod1 to Mod2
    - Results are promising!
- Currently processing data that was collected in January 2026 and preparing for further research tests with this cloud
- Stay tuned for official published paper offering this as a calibrated cloud in the IRT!

Propulsion Systems Laboratory (PSL)

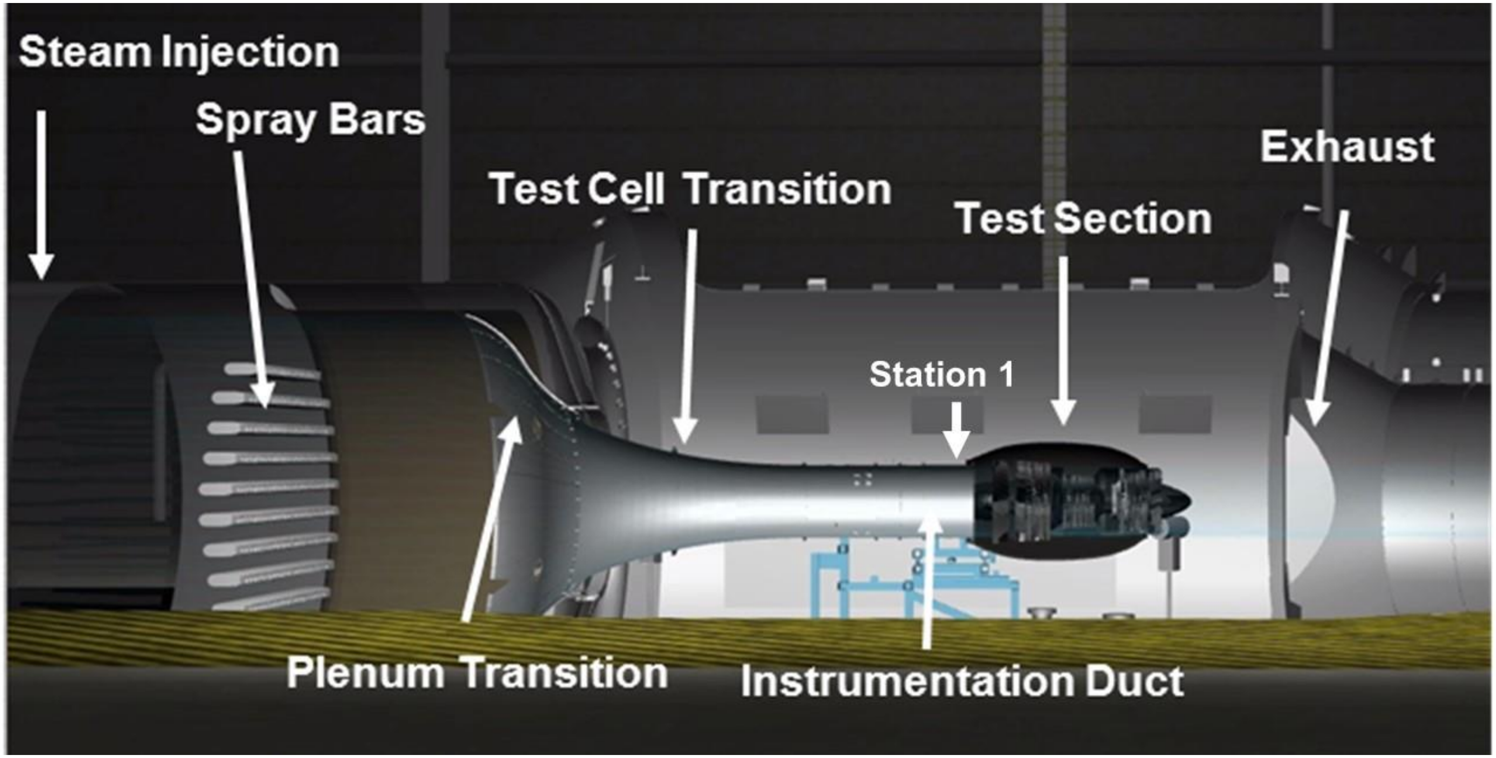
NASA's only ground-based test facility that provides true flight simulation for experimental research on full-scale, air-breathing, propulsion systems

- Facility Parameters
- -Altitude (tank pressure)
- -Mach Number (inlet pressure)
- -Inlet Temperature
- -Humidity *(optional)*

- with Icing (Test Cell 3 only)
- -spray nozzle air and water pressure
- -spray nozzle air and water temp
- -particle size
- -total water content
- -ICI or SCL

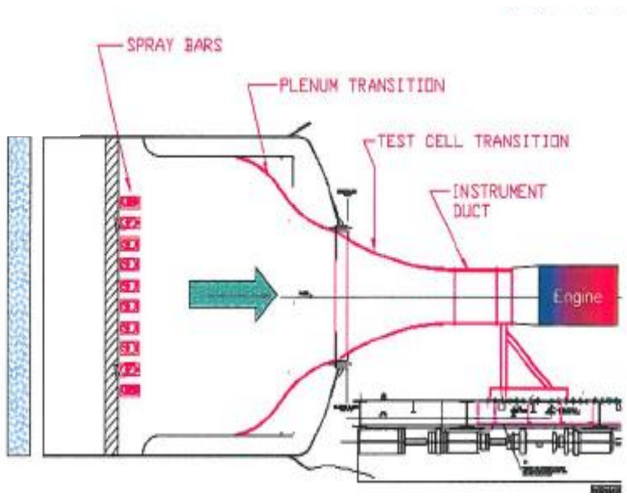


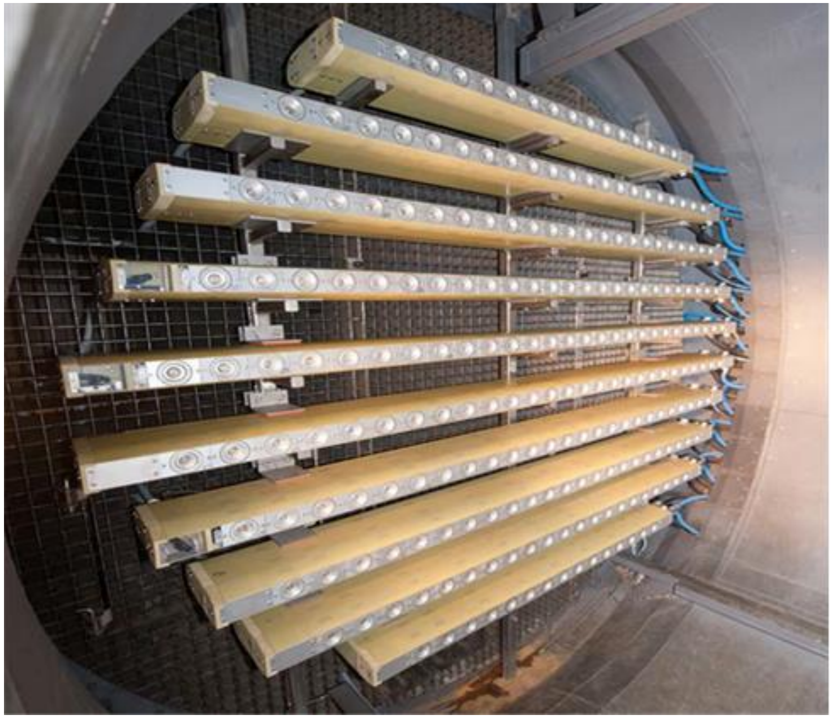
PSL Test Cell 3 – General Layout



PSL Icing Overview

- 2011: added the capability to simulate atmospheric conditions
  - ice crystals, liquid water droplets, and mixed phase
- PSL-3: Altitude engine icing test cell layout
  - Spray bars
  - Transition Duct (s)
  - Instrumentation Duct and Tomography Duct
  - Calibration Instrumentation or a Test Article





PSL Icing Characterization Test Program Focus

- Calibration is done per test
- Work with customer's CPA (critical point analysis) to calibrate specific envelope of test points
- Focal points:
  - 14 CFR 33.68: Induction System Icing Certification Requirement
  - 14 CFR Part 25 Appendix C: Atmospheric Icing Conditions
  - 14 CFR Part 29 Appendix C: Icing Certification Continuous and Intermittent Maximum Conditions
  - 14 CFR Part 33 Appendix D: Mixed Phase and Ice Crystal Icing Envelope (Deep Convective Clouds)
  - AC 20-147A: Guidance for Demonstrating Compliance, Engine Induction System Icing Certification

Cloud Calibration

- Study icing cloud parameters including:
  - Water content (e.g. TWC, IWC, LWC)
  - Particle size distribution
  - Air temperature
  - Humidity
  - Phase
  - Cloud uniformity
- In-house icing physics simulations help generate “starting points”
- DOE analysis
  - optimize test time
  - statistically significant number of test points

Thank You!

- Presentation Content:
  - Aaron Johnson (Amentum)-SPC charts for uniformity
  - Patrick Rachow (HX5 Sierra)-PSL
  - Alicia Graham (NASA)-PSL
  - Tadas Bartkus (Ohio Aerospace Institute)-PSL
  - Ru-Ching Chen (NASA)-droplet splash video
  - Laura Hux (Amentum)-Dropsize probe comparison
- Aeroscience Evaluation and Test Capabilities (AETC) portfolio office
- Engineering and Technician Staff at IRT
- Icing Branch Researchers
- Engineering and Technician Staff at PSL