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Presented by: Judy Van Zante

NASA Glenn Research Center

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## PSL Icing Session

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<td>2:00 PM</td>
<td>Turbofan Ice Crystal Rollback Investigation and Preparations Leading to the Second, Heavily Instrumented, Ice Crystal Engine Test at NASA PSL-3 Test Facility</td>
<td>R. Goodwin</td>
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<td>Determination of engine recovery after an ice accretion rollback, engine performance deterioration and health monitoring using minimal instrumentation during icing testing at NASA Glenn PSL-3</td>
<td>D. Walker</td>
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<td>3:00 PM</td>
<td>Preliminary Results from a Heavily Instrumented Engine Ice Crystal Icing Test in a Ground Based Altitude Test Facility</td>
<td>A. Flegel</td>
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<td>Modeling of Highly Instrumented Honeywell Turbofan Engine Tested with Ice Crystal Ingestion in the NASA PSL</td>
<td>J. Veres</td>
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<td>4:00 PM</td>
<td>Test Point Selection for Engine Crystal Icing Test at NASA PSL-3 for focused sensitivity, peak intensity, and anti-ice evaluations</td>
<td>D. Dischinger</td>
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<td>5:00 PM</td>
<td>NASA Glenn Propulsion Systems Lab Ice Crystal Cloud Characterization Update (2015)</td>
<td>J. Van Zante</td>
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<td>Aircraft engine icing instrumentation used in the NASA Glenn Propulsion Systems Laboratory</td>
<td>T. Bencic</td>
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Outline

• Facility Description
• Cloud Characterization Parameter Space
• Aspects Characterized
• Conclusions
PSL Facility

Aero-Thermal Duct  Tomography & Raman  Cloud Calibration Duct

Configuration 1:
- Engine
- 27:1 CR

Configuration 2:
- Component
- 11:1 CR
- 22:1 CR with bullet nose*
  * approx. representation

NAIA Aviation - 6th ASE Conf., Jun 2016
PSL Parameter Space

**Airflow Conditions**
- (Duct Geometry)
- Pressure Altitude, $P_0$
- Mach, Air Mass Flow Rate, $W_a$
- Temperature, $T_{PL}$
- Relative Humidity, $R_{HPL}$

*PSL is Isentropic & Adiabatic

**Spray Conditions**
- Nozzle Type & #: Mod1, Std
- Water Pressure, $P_{wat}$
- Air Pressure, $P_{air}$
- Air/Water Temp, $T_{air}$, $T_{wat}$
- Water Source: City, DI
- Spraybar Cooling Air and Pressure

Physics of the Process:
- Liquid water issues from the spraybars.
- Water particles immediately start to evaporate.
- Particles start to chill/freeze as they travel through the plenum and into the contraction.
- The vapor …
Setting Conditions

Customer Provides
Ranges at Plane of Interest (inlet to Fan or Booster):
- \( P_s \), static pressure
- \( T_s \), static temperature
- Mach
- Altitude
- TWC, Total Water Content
- MVD (Particle Size)

NASA Actions
- Calculate \( W_a \) to set Facility Conditions
- Characterize Spray Conditions
- Phase of particles at Sta 1 primarily a function of wet bulb Temp, Twb. New model to predict (T. Bartkus).
PSL Cloud Characterization Envelops

Two regions of conditions simulated
- Engine Fan Face (Honeywell Engine Tests LF01 & LF11)
- Aft of Fan / Inside Booster (Fundamental Ice Crystal Icing Study, Struk et. al)
PSL Cloud Characterization Process

- Cloud Uniformity
- Total Water Content
  - Measurements in Center
  - Bulk average in Cross-Section
- Particle Size
- Particle Phase and Temperature - *T. Bencic will cover next talk.*
Cloud Uniformity

AIAA’s 2014 Van Zante & 2015 Bencic et.al: Good agreement between these three methods.

Tomography is the diagnostic of choice.

Grid  Laser Sheet  Tomography
**Tomography – near real-time monitoring**

**Procedure:**
- Measure light extinction with cloud OFF (baseline)
- Measure light extinction with cloud ON (extinction due to size and number of particles)
- Intensity Ratio, $I_{ij}$, output at every ‘pixel’ (i, j)
- Calculate avg Intensity Ratio over 1x1-in Center, $I_{00}$
- Calculate Concentration Factor, CF, $I_{00}/\sum I_{ij}$
Total Water Content: Measurements

Multi-Wire (MW)  Robust Probe (RP)  Iso-Kinetic Probe (IKP2)

All measurements at Duct Center, TWC_{00}
MW and RP Notes

- Meas. power to evap. impinging water
- Minimize flow angularity into MW head
- Correct for Collection (Collision) Efficiency, MW only. Effects of particle bouncing, splashing not accounted for.
- Track default TWC (100% liquid)
- Added iWC (100% ice crystal)

\[
TW C = \frac{K \cdot P_{wet}}{[c_{lq}(T_{evap} - T_{amb}) + L_{evap}] \cdot VTAS \cdot L \cdot W}
\]

\[
iWC = \frac{K \cdot P_{e_{wet}}}{[c_{ice}(T_{0} - T_{amb}) + L_{fus} + c_{lq}(T_{evap} - T_{amb}) + L_{evap}] \cdot VTAS \cdot L \cdot W}
\]

- iWC / TWC ~ 0.88
IKP Notes

- Iso-kinetically ingests air and cloud particles (no gain or loss of mass)
- Evaporates all cloud particles, regardless of phase; measures total water vapor
- Independent measure of background water vapor is subtracted so that only Ice + Liquid phases are calculated.

- At PSL, several sources of water vapor measurements at Sta 1. Largest correction applied.
- At PSL, a radial profile of water vapor was observed (Fundamental Ice Crystal Icing Study, P. Struk, 3/2016)
Sample TWC time traces

MW
RHPL Sweep
& Melt Ratio

IKP2
RHS1
Total Water Content: Bulk_Water Flow

Simple Calculation based on injected Water Flow Rate, \( Wf \), Air Mass Flow Rate, \( Wa \), and Sta 1 statics. Constant \( C \) includes density of water. Assume uniform distribution across Sta 1 Duct.

\[
Wf \text{ (gal/min)} = \#Noz \times Cfn \times \sqrt{(\Delta P)}
\]

\[
TWC_{Wf} \text{ (g/m}^3\text{)} = C \times Wf \times Ps1 \div (Wa \times Ts1)
\]

If add a cloud Displacement or Boundary Layer thickness \( \delta \)

\[
TWC_{WfBL} \text{ (g/m}^3\text{)} = C \times Wf \times Ps1 \div (Wa \times ((R-\delta)/R))^2 \times Ts1)
\]

\( TWC_{Wf} \) is the basis function for TWC measurements

\( TWC_{WfBL} \) was recommended for LF01 and LF11 Tests
Total Water Content: Bulk_Meas

• Combine Measured TWC\(_{00}\) and Tomography CF.

\[
\text{TWC\_Bulk\_Meas (g/m}^3\text{)} = \frac{\sum (I_{ij} \times (TWC_{00}/I_{00}) \times A_{ij})}{\sum A_{ij}}
\]

• Created a CF curve fit based upon Pair and TWC\_Wf, TWC\_Bulk\_Fit

![Graphs showing TWC Bulk Fit for IKP, RP, and MW](image-url)
TWC & radial distribution of particle size

- Scatter in data due to radial MVD effect. CFD predicts larger particles concentrated at center, while smaller particles more uniformly distributed.
- This radial MVD profile is not currently incorporated into the tomography intensity ratios.

![Graph showing TWC_Bulk_Fit and TWC_WF](image)

![Graph showing TWC_Bulk_Fit with MVD groups](image)

Distribution of particles:
- 20 um
- 100 um

 IKP TWC_Bulk_Fit

 IKP TWC_Bulk_Fit (MVD groups)
TWC Bulk Comparison

IKP + Tomography ≈ Water Flow + Boundary Layer

Bulk TWC

TWC_Bulk_Meas

TWC_Wf_BL

With the same boundary layer thickness assumption, and same basis formulation, TWC_Wf

IKP: Closer to “true” TWC

MW: Closest link to 1998 ALF502 Flight Campaign

Used in LF01 and LF11
Particle Size: Measurements

Cloud Droplet Probe (CDP)  
Refracted + Diffracted Light

Cloud Imaging Probe (CIP-GS)  
Shadowing

All measurements at Duct Center.  
Future ability to shift off-center
CDP + CIP Particle Size Distributions

Sample PSD: For the CDP survey, Tair, Twat & TPL were ‘warm’. For the CIP survey, Tair, Twat & TPL were at test conditions, ‘cold’. Same Alt, Mach and RHPL.

Pair = 20 psid, DeltaP = 175 psid; MVD = 80 um
Mod-1 MVD Curve Fit

For LF11 MVD sweeps: Given a Pair line, increase DeltaP. This “guarantees” an increase in MVD, even if exact values are not known.
Additional PSD Measurements

Both PDI and HSI are non-intrusive. Have taken data in two most recent efforts at center and off-center. Will be reported in future.

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Phase Doppler Interferometer (PDI)
- Particle size (liquid only)
- Particle velocity
- Number density
- LWC

High Speed Imager (HSI)
- Particle size (ice & liquid)
- Shape
- Number density
- TWC
Particle Phase and Temperature

- Raman Spectra can evaluate bonded structure of water in both liquid and solid phases, as well as temperature.
- Benchtop success
Particle Phase, Temperature - Raman

- “Point” measurement at beam waist
- Some success in PSL, with particles moving at 0.5 Mach
- Continuing development

![Diagram](image)

**Raman Water Spectra**

- Indicates presence of liquid water
- Absence of liquid water
Conclusions

• Cloud Cal Space is 12-parameters with complex interactions

• Radial variations (concentrations in center) noted in
  - TWC, total water content
  - PSD, particle size distribution
  - RH, relative humidity

• Near-independent verification of Bulk TWC measurement:
  IKP2 + Tomography within 5% of Water Flow with Boundary Layer

• Lowest confidence measurement is ice crystal PSD, MVD. Actively investigating alternate methods.

• Some success with measuring Particle Phase, Temp. via Raman Spectroscopy