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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

Sta 1
PSL Parameter Space

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

*PSL is Isentropic & Adiabatic*

**Spray Conditions**
- Nozzle Type & #: Mod1, Std
- Water Pressure, $P_{wat}$
- Air Pressure, $Pair$
- 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):
- Ps, static pressure
- Ts, static temperature
- Mach
- Altitude
- TWC, Total Water Content
- MVD (Particle Size)

NASA Actions
- Calculate Wa 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).
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, TWC₀₀
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)

\[
TWC = \frac{K \cdot P_{wet}}{[C_{liq}(T_{evap} - T_{amb}) + L_{evap}] \cdot VTAS \cdot L \cdot W}
\]

\[
iWC = \frac{K \cdot P_{iwc}}{[C_{ice}(T_0 - T_{amb}) + L_{fus} + C_{liq}(T_{evap} - T_{amb}) + L_{evap}] \cdot VTAS \cdot L \cdot W}
\]

- \(\text{iWC} / \text{TWC} \sim 0.88\)

SEA, Inc. WCM-2000 User’s Manual
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

Twb (F) =

28  32.1  30.4  31.1  31.6  34.5

MW
RHPL Sweep & Melt Ratio

IKP2
RHS1
Total Water Content: Bulk_Water Flow

Simple Calculation based on injected Water Flow Rate, $W_f$, Air Mass Flow Rate, $W_a$, and Sta 1 statics. Constant $C$ includes density of water. Assume uniform distribution across Sta 1 Duct.

$$W_f \text{ (gal/min)} = \#\text{Noz} \times C_{fn} \times \sqrt{\Delta P}$$

$$\text{TWC}_{\text{Wf}} \text{ (g/m}^3\text{)} = C \times W_f \times P_{s1} / (W_a \times T_{s1})$$

If add a cloud Displacement or Boundary Layer thickness $\delta$

$$\text{TWC}_{\text{Wf BL}} \text{ (g/m}^3\text{)} = C \times W_f \times P_{s1} / (W_a \times ((R-\delta)/R)^2 \times T_{s1})$$

$\text{TWC}_{\text{Wf}}$ is the *basis function* for TWC measurements

$\text{TWC}_{\text{Wf BL}}$ was recommended for LF01 and LF11 Tests
Total Water Content: Bulk_Meas

- Combine Measured TWC₀₀ and Tomography CF.
  \[ \text{TWC\_Bulk\_Meas (g/m}^3\] = \[ \sum (I_{ij} \times (TWC_{00}/I_{00}) \times A_{ij}) / \sum A_{ij} \]
- Created a CF curve fit based upon Pair and TWC_Wf, TWC_Bulk_Fit
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.
TWC Bulk Comparison

IKP + Tomography ≈ Water Flow + Boundary Layer
Bulk TWC
TWC_Bulk_Meas

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

**Raman Water Spectra**

- Indicates presence
- Absence of liquid water

![Raman Water Spectra Graph](image)
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