NASA EIWG PSL and Analytical Tools Presentation

Ashlie Flegel
NASA Glenn Research Center
EIWG Meeting May 11-12, 2017
Arlington, VA

Propulsions Systems Laboratory Capability Roadmap

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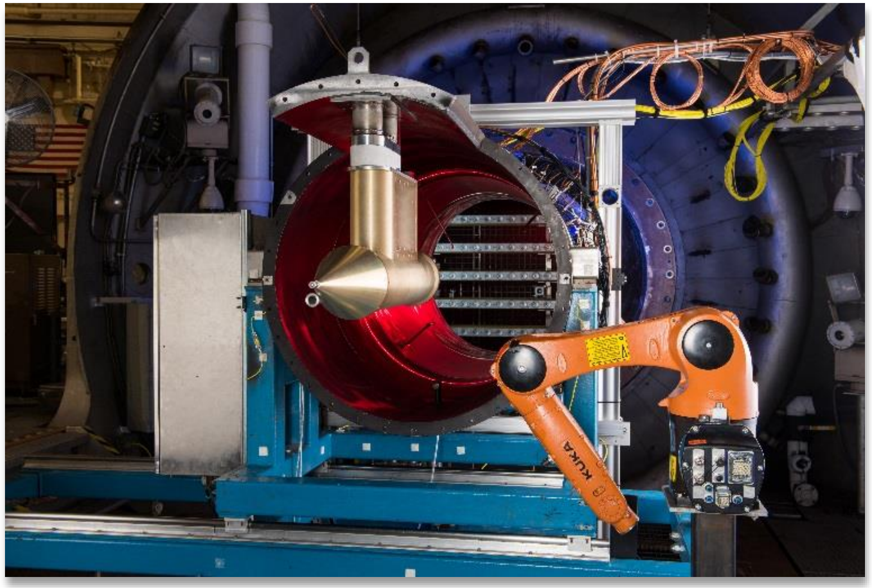
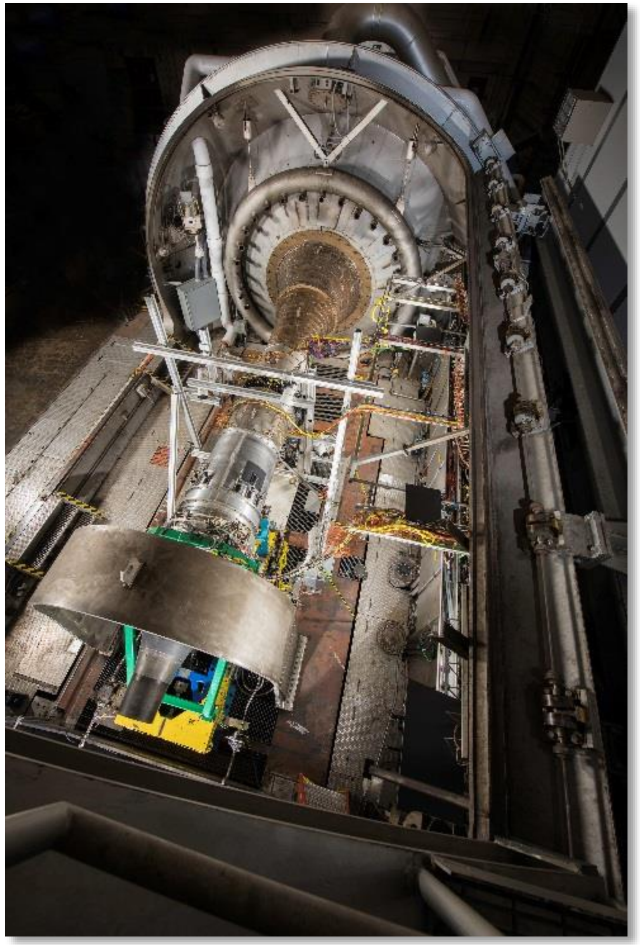
Aeronautics EVALUATION and TEST Capabilities Project
The Right Facility at the Right Time





Outline

- Goals
- Roadmap Overview
- Update on EIWG requirements
- Status

What is the function of the PSL icing facility?

To provide world class testing of turbofan engines and driven rigs, exploring the effects of Ice Crystal Icing. This facility can provide data that can be used to:

- Simulate the flight environment conditions that are seen inside the engine.
- Understand the physics of ICI
- Develop models and tools
- Goal: Data can be used for certification, similar to the NASA Icing Research Tunnel.

Propulsions Systems Laboratory

- Since 2013:
  - 2 full engine tests
  - 1 driven rig test
  - 1 fundamental test – included cloud characterization
  - 4 cloud calibrations
- In 2017:
  - 1 cloud calibration
  - 1 engine test
  - 1 fundamental test

How does NASA continue to develop PSL's capability?

AETC Project Challenge:
Demonstrate an Advanced Operational Capability for PSL Engine Icing Testing

- Objective: Ensure PSL can simulate High Ice Water Content cloud conditions experienced in nature to the degree required to simulate engine failure modes by FY20.

- Major Outcomes:
  - ❑ Ability to simulate an ice crystal engine icing environment to the degree required and test methodologies for engine development activities.
  - ❑ Ability to develop, test, and validate engine icing software codes and diagnostic instrumentation.
  - ❑ Reduce costly and dangerous engine icing flight testing in ice crystal conditions.

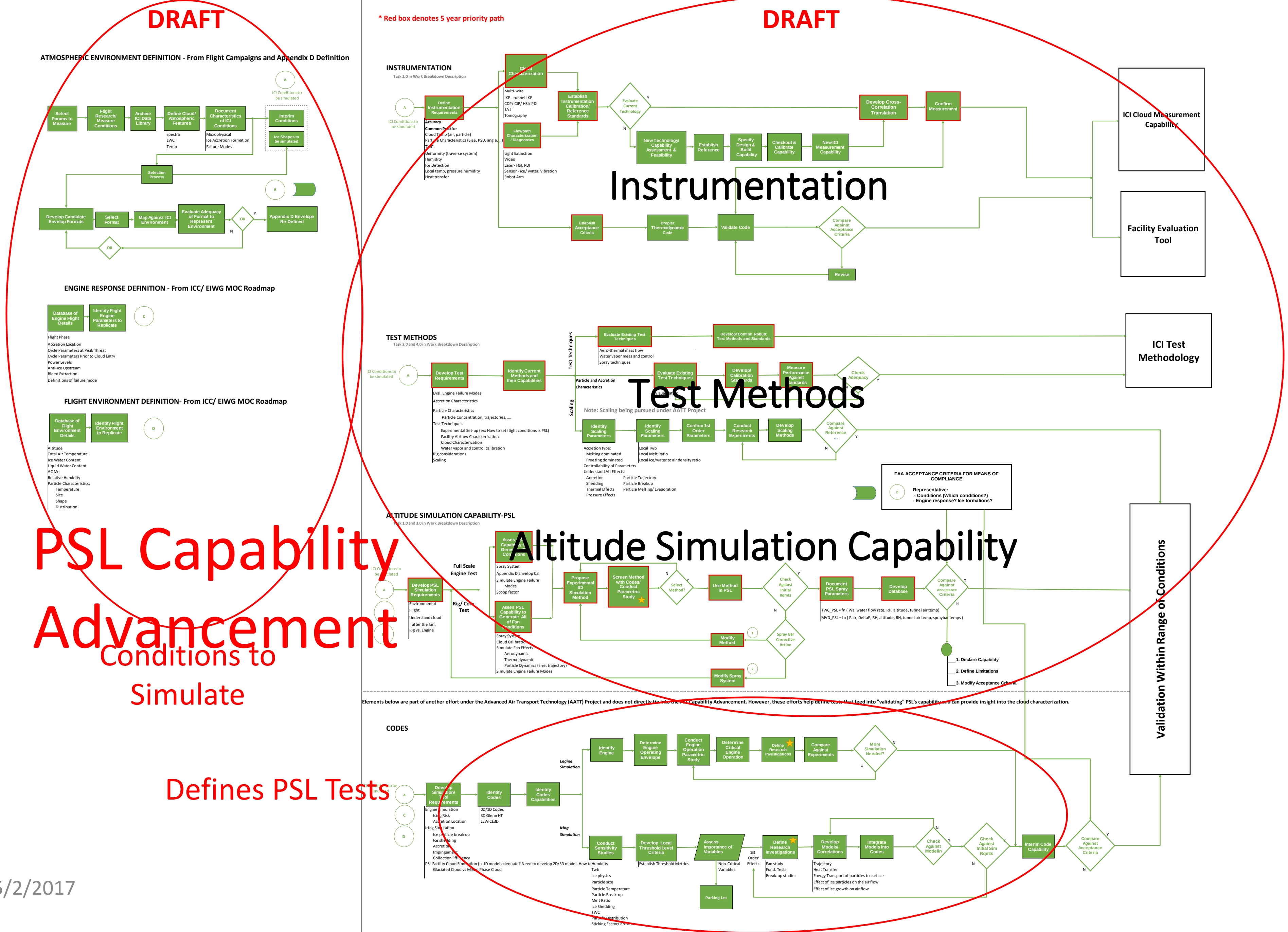
- Maturity: At the completion of this capability challenge, PSL will provide ice crystal icing conditions at altitude for various full scale engine classes and simulate engine icing failure modes for engine and engine component development.

5 Year Focus

- Instrumentation to measure IC Cloud upstream and inside test hardware flow path.
- Characterize PSL Cloud
- Standardize PSL Icing Test Methodology
- Understand the differences between PSL Cloud and natural environment ingested in the engine.

NASA AETC PSL Capability Roadmap

A. Flegel 12/07/2016
Version: 7



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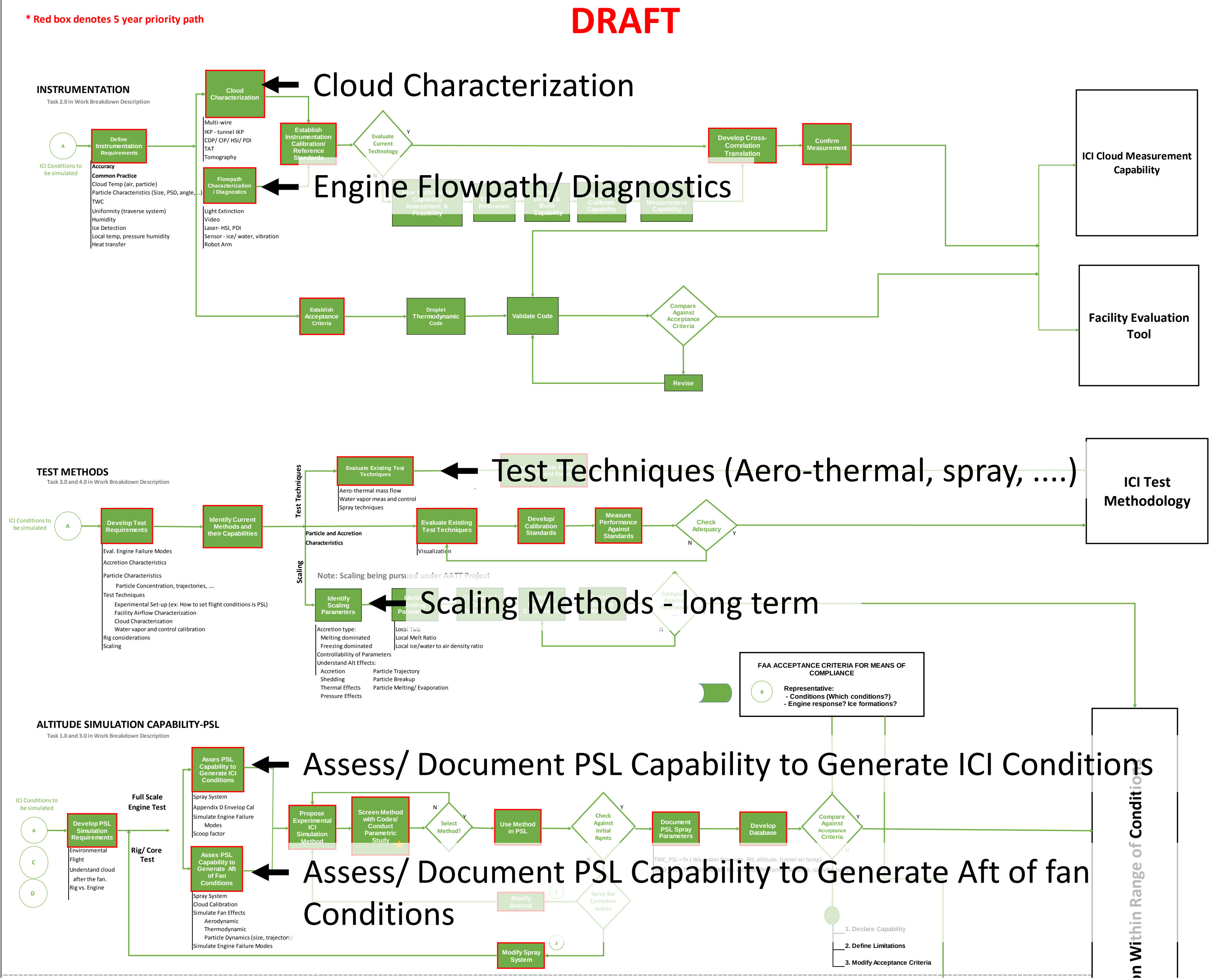


Instrumentation

Test Methods

Altitude Simulation Capability

Requirements for an Altitude Engine Test

- Particle Temperature: Compensate for particle temperature at ambient altitude.
  - Two techniques being pursued at NASA. A Raman Scattering Surface Water probe was used during the LF11,4th Cloud Calibration, and Fundamental Test. A fluorescence technique has been explored with minimum success.
  - Potential FY19 NRA solicitation to pursue a particle measurement method for both PSL and IRT.
  - Fundamental Test?........*What role ice particle temperature plays in the accretion process.* Need a method to measure. *Does temperature affect breakup and erosion?*
- Particle Size Distribution: Compensate for lack of fully glaciated distribution that the atmosphere provides.

  Particle Shape and Mechanical Properties: What are the natural shapes and do they affect melting.
  - During next test PSL is attempting acquire particle size measurements aft of a fan.
  - Potential FY19 NRA solicitation to pursue fan test for impact/ break up model development
  - There have been internal discussion about acquiring validation data through a flight test.
- Relative Humidity: PSL uses a 50% RH in order to achieve glaciation. How to compensate?
- Identify susceptible locations: What type of instrumentation and accuracy needed.
  - 0D/1D COMDES code is being developed to identify flight conditions and susceptible flowpath location with icing risk. In future work this would drive instrumentation placement.
  - Engine and Fundamental test have enabled the exploration of various instrumentation and test techniques which are being evaluated.
- Identify methods to measure/ control critical environmental characteristics in test cell: Document uniformity, repeatability, reliability of instruments (do they have collection η?)
  - On-going. The 2017 AIAA Aviation papers on the fundamental test will have useful information on the PSL characteristics.
- Transients in alt facility–Not an area NASA is exploring
- Define minimum environmental exposure –Not an area NASA is exploring
- CPA, narrow down scope of test – Not an area NASA is exploring

Requirements for an Altitude Rig Test

- Particle Temperature: Need to simulate engine fan discharge while ice particle is still near ambient.
  - *What role ice particle temperature plays in the accretion process and impact of fan stage on ice particles including wetness due to melting*
- Particle Size and Shape Distribution: Characterize the fan/ front stage breakup for various size and shape.

  Particle Radial Distribution Profile: What effect does the fan and spinner have on the particle distribution at the core inlet.
  - During next test PSL is attempting acquire particle size measurements aft of a fan.
  - Potential FY19 NRA solicitation to pursue fan test for impact/ break up model development
  - There have been internal discussion about acquiring validation data through a flight test.
- Instrumentation to measure ice thickness, quality, etc..
- Relative Humidity: PSL uses a 50% RH in order to achieve glaciation. How to compensate?
  - Fundamental Test?........ *What role does humidity play in the accretion process?*
- Identify susceptible locations: What type of instrumentation and accuracy needed.
  - 0D/1D COMDES
- Identify methods to measure/ control critical environmental characteristics in test call: Document uniformity, repeatability, reliability of instruments (do they have collection η?)
  - On-going. The 2017 AIAA Aviation papers on the fundamental test will have useful information on the PSL characteristics.
- Develop instrumentation/ measurement techniques to evaluate accretion inside of engine.
  - This work is being pursued.
- Transients in alt facility: difficult to simulate the icing event triggered by engine throttle movement due to absence of fan and HP spools. –Not an area NASA is exploring
- Define minimum environmental exposure –Not an area NASA is exploring
- CPA, narrow down scope of test – Not an area NASA is exploring
- Rig test results are not absolute indication of certification compliance: further analyses are required to show rig test results demonstrate compliance. – Not an area NASA is exploring

Measure of Success By End of AETC PSL CA

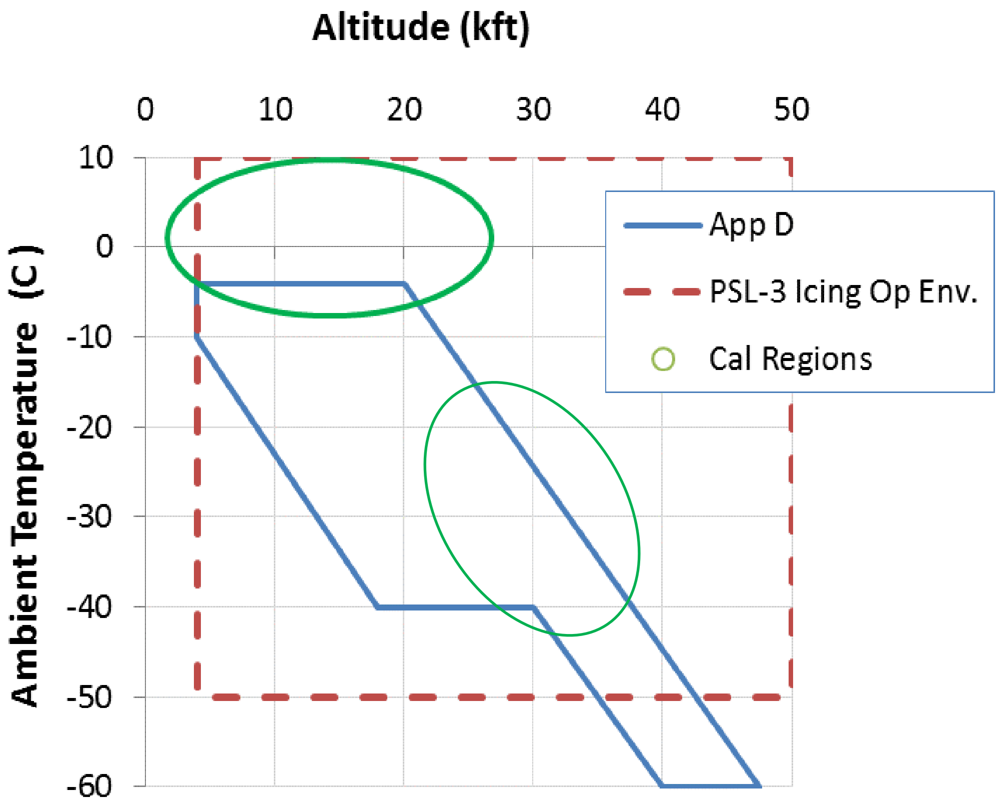
- TM Documents
  - Detailed Facility Description
  - Cloud Characterization
  - Aero-thermal Calibration

- Integrate PSL methodology in a recommended practice

- Have completed several engine tests (different classes) and/ or additional driven rig test

PSL Cloud Characterization Elements

- Cloud Uniformity
- Total Water Content
    - Measurements in Center
    - Bulk average in Cross-Section
    - Radial profile
- Particle Size
- Particle Phase and Temperature
- Water vapor radial profile
- Temperature radial profile



PSL Calibrated Regions

PSL Parameter Space

Airflow Conditions

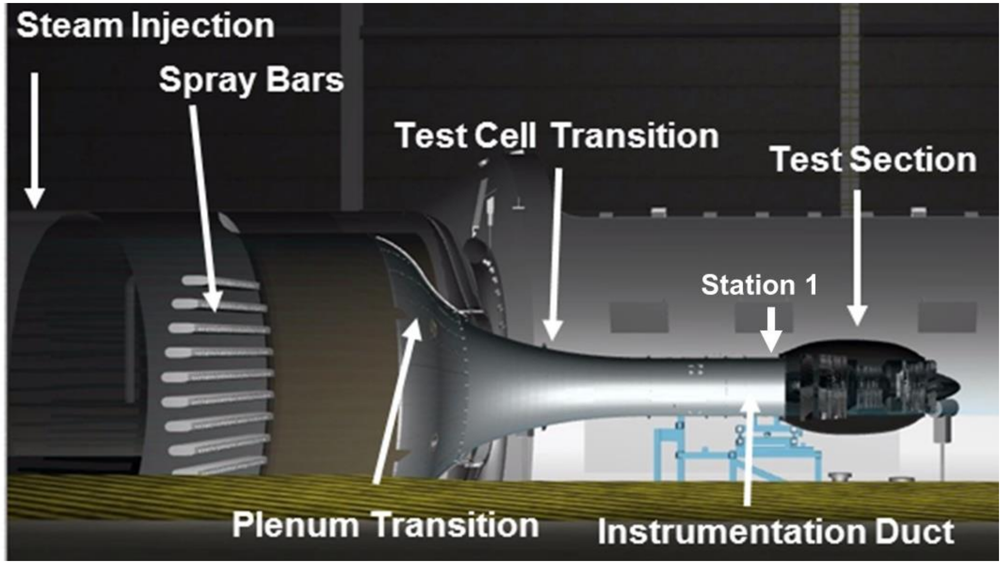
- Duct Geometry
- Pressure Altitude, *P0*
- Temperature, *TPL*
- Mach, Air Mass Flow Rate, *Wa*
- Relative Humidity, *RHPL*

PSL is Isentropic & Adiabatic

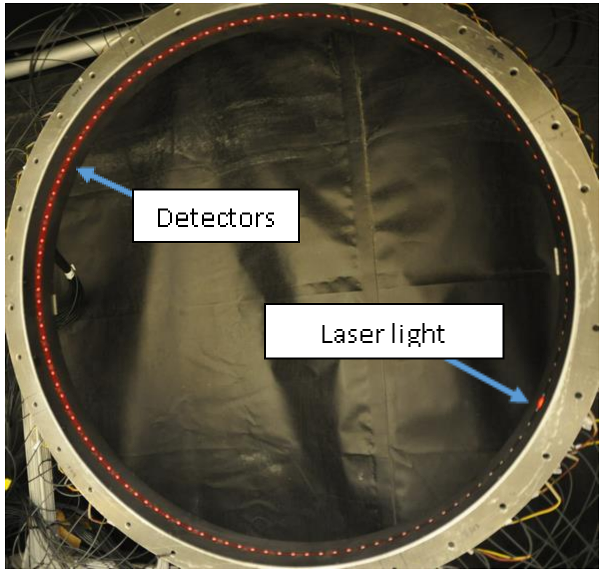
Spray Conditions

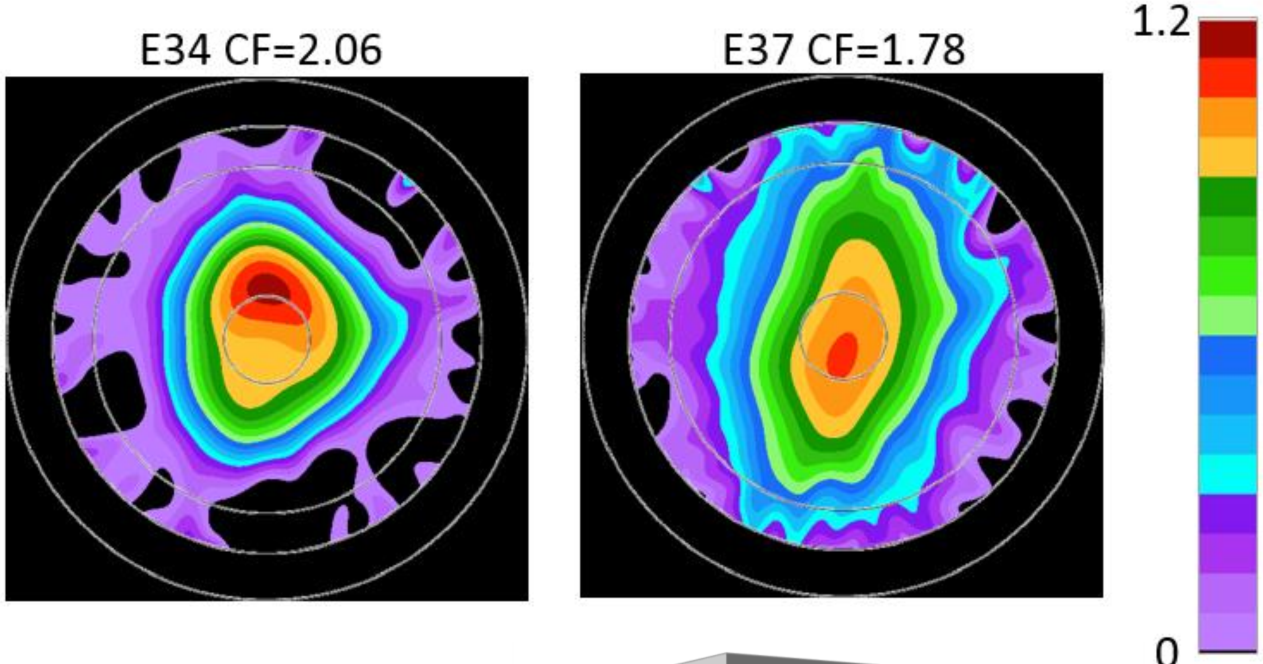
- Nozzle Type & #: Mod1, Std
- Water Pressure, *Pwat*
- Air Pressure, *Pair*
- Air/Water Temp, *Tair, Twat*
- Water Source: City, DI
- Spraybar Cooling Air Temp and Pressure

<u>Physics of the Process</u>:
- 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 …



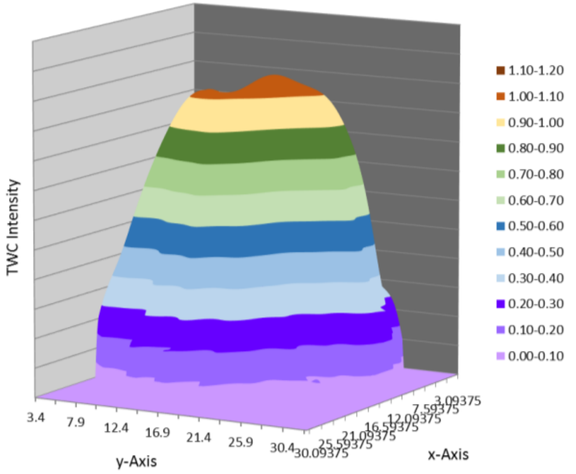
Cloud Uniformity Tomography – near real-time monitoring





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, $I_{00}/\sum I_{ij}$

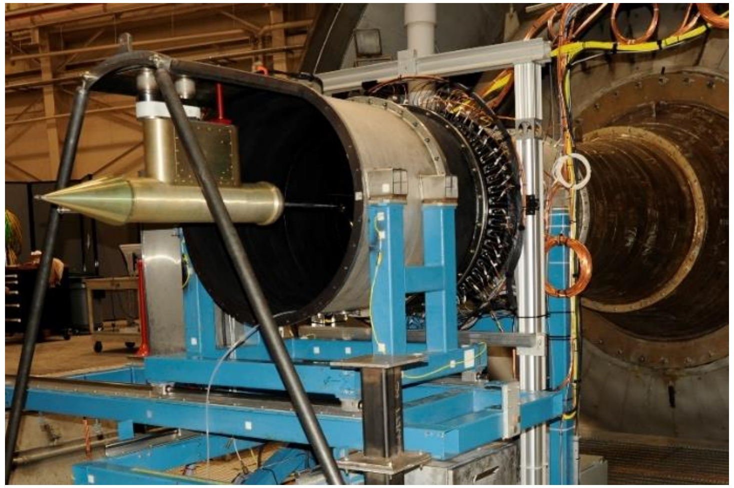


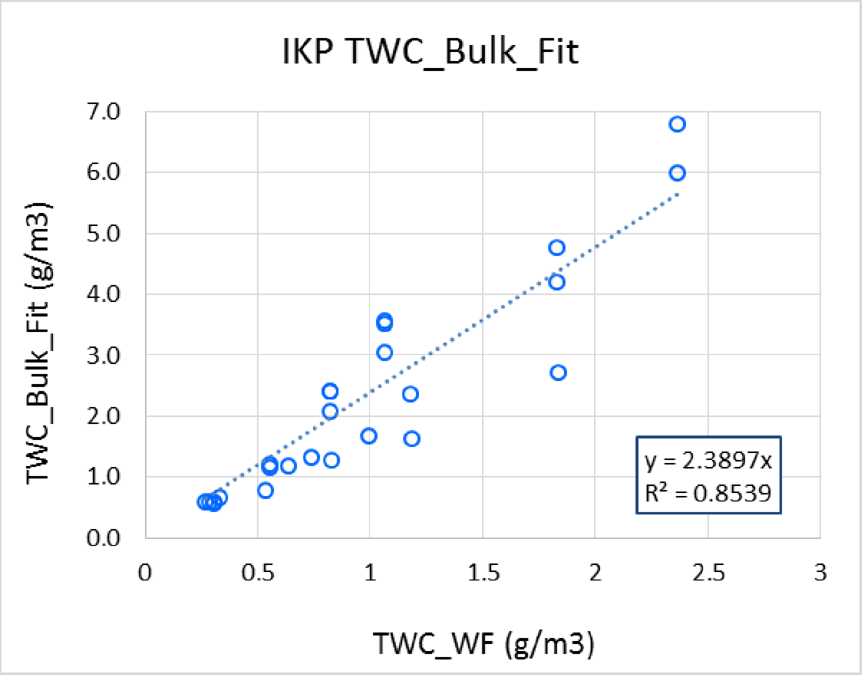
Total Water Content (TWC)

- Have used Multi-wire, Robust Probe, and Iso-Kinetic Probe to measure TWC at Duct Center.
- Standard measurement: IKP2
- Measured TWC:
  - Combine Measured TWC_{00} and Tomography Concentration Factor.

    $TWC\_Bulk\_Meas\ (g/m^3) = \sum (I_{ij} * (TWC_{00}/I_{00}) * A_{ij}) / \sum A_{ij}$
  - Created a curve fit based upon Pair and TWC_Wf, TWC_Bulk_Fit
- Calculated TWC:
  - Calculation assuming uniform distribution over entire duct based on measured:
    - Water flow rate (W_f)
    - Air mass flow rate (Wa)
    - Station 1 static pressure and temperature

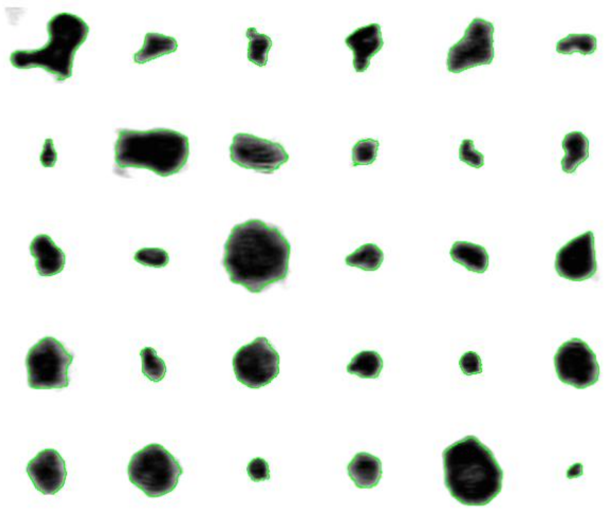
$$TWC\_W_f = C * W_f * P_{s,1}/Wa * T_{s,1}$$



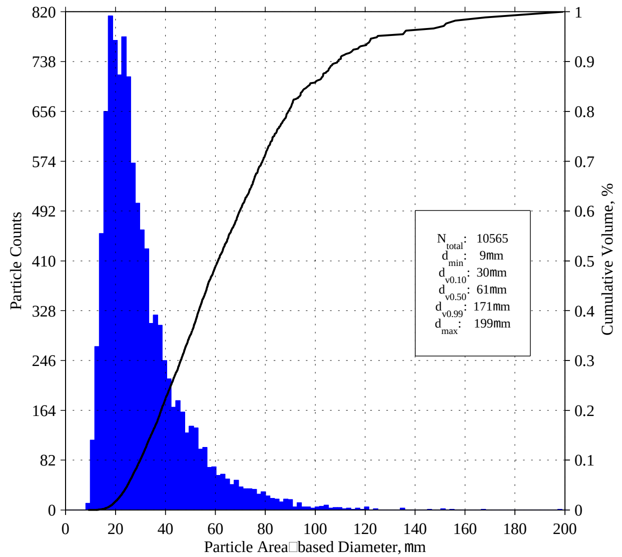


Particle Size Measurement Tools

- Cloud Droplet Probe (CDP)
  - 2 to 50 µm
  - Forward scattering technique
  - Uncertainty about accuracy with ice (and mixed phase)
- Cloud Imaging Probe (CIP)
  - 15 to 930 µm
  - Shadowing technique
  - Confidence with ice and water (and mixed phase)
  - Can get overwhelmed if # density is too high
- High Speed Imager (HSI)
  - ~10 to 860 µm
  - Confidence with ice and water (and mixed phase)
  - Better suited for larger particle distributions (clipped below ~10 µm)
- Phase Doppler Interferometer (PDI)
  - 0.5 to ~1000 µm
  - Only confidence with water
  - Scatter of data means ice, but cannot provide good particle size if not liquid

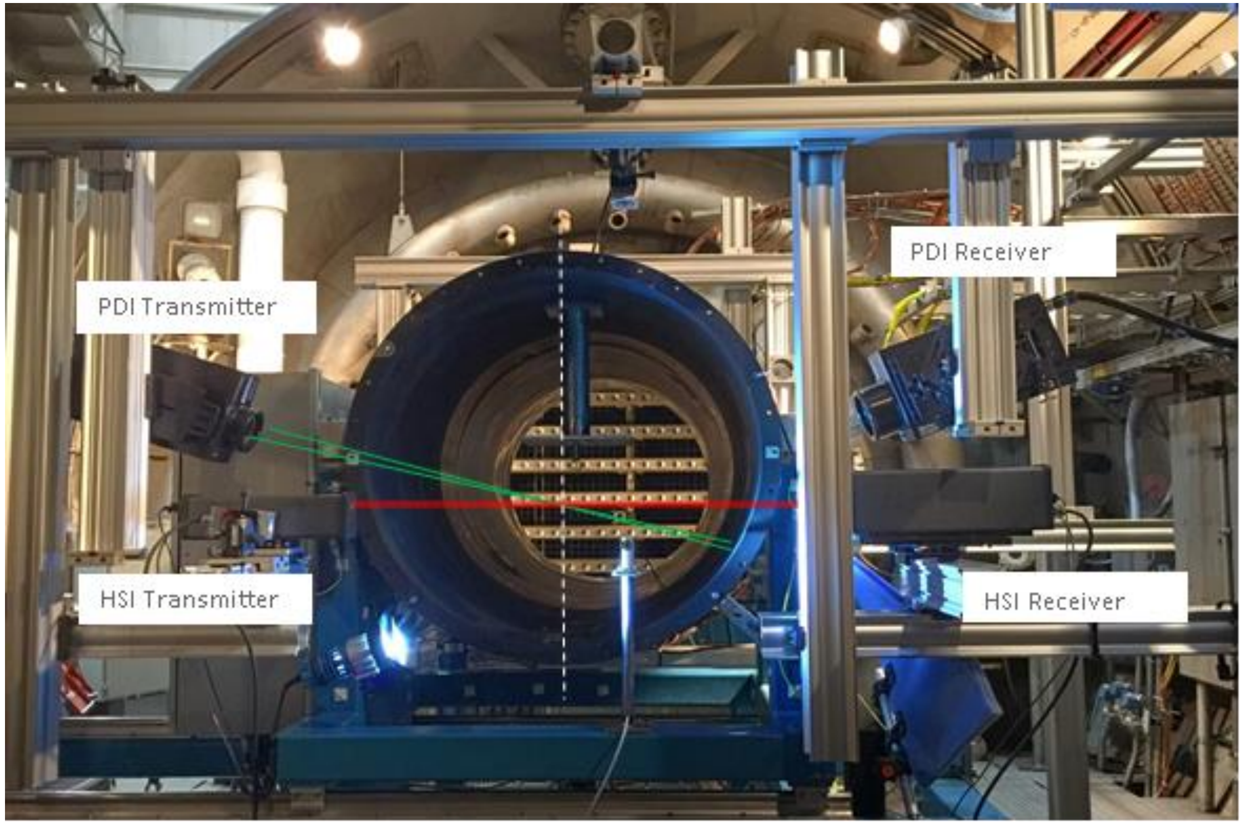


1st Fund. ICI Test – Test Point 236 Particle Image Sample



1st Fund. ICI Test – Test Point 236 PSD Quick Summary

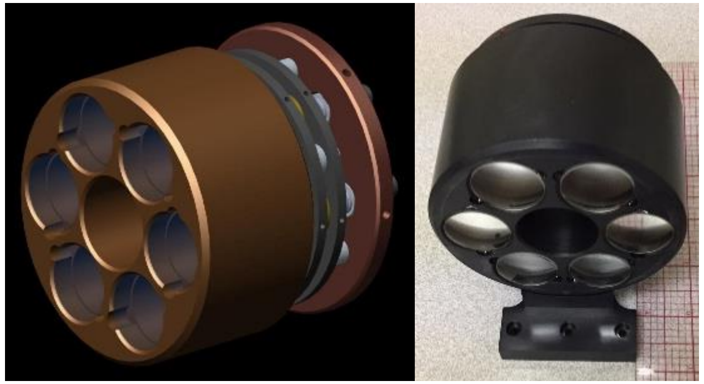
Particle Size Measurements



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

High Speed Imager - HSI
- Particle size (ice & liquid)
- Shape
- Number density

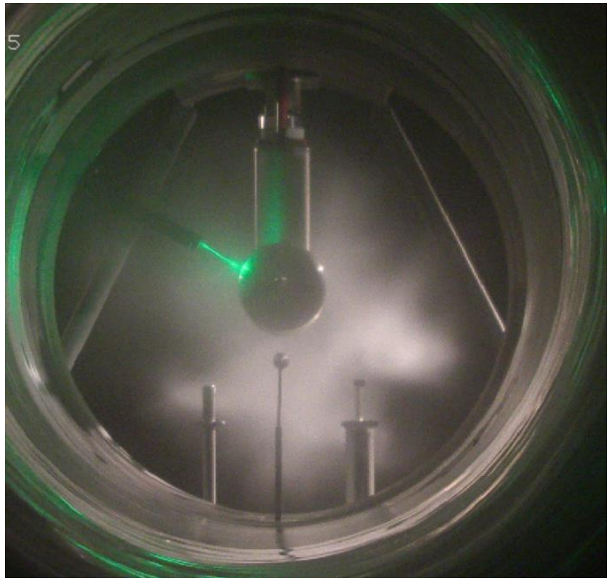
HSI Receiver – 2nd Gen. Modular Unit (Cassegrain Telescope with CMOS Camera – 0.5m focal range)

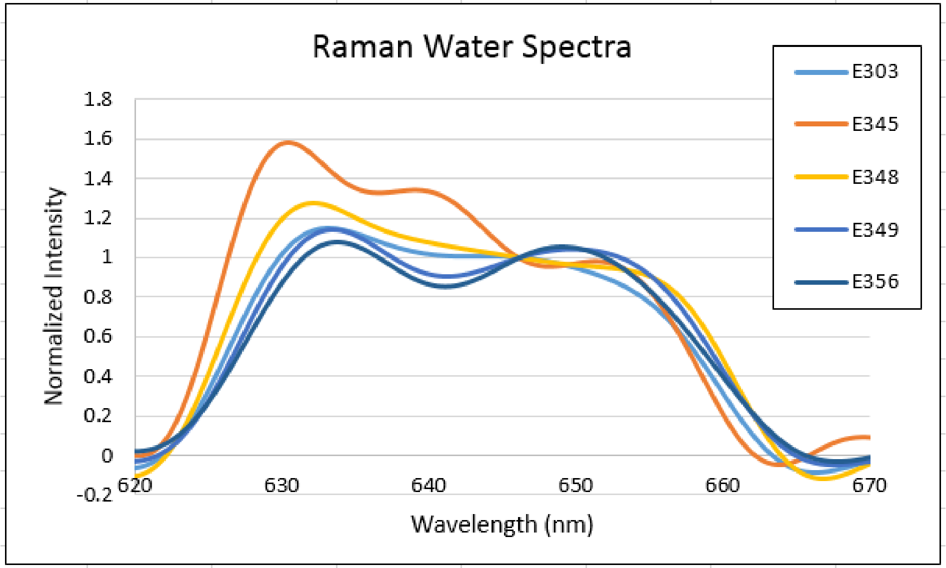


HSI Transmitter – 2nd Gen. Modular Unit (improved illumination)

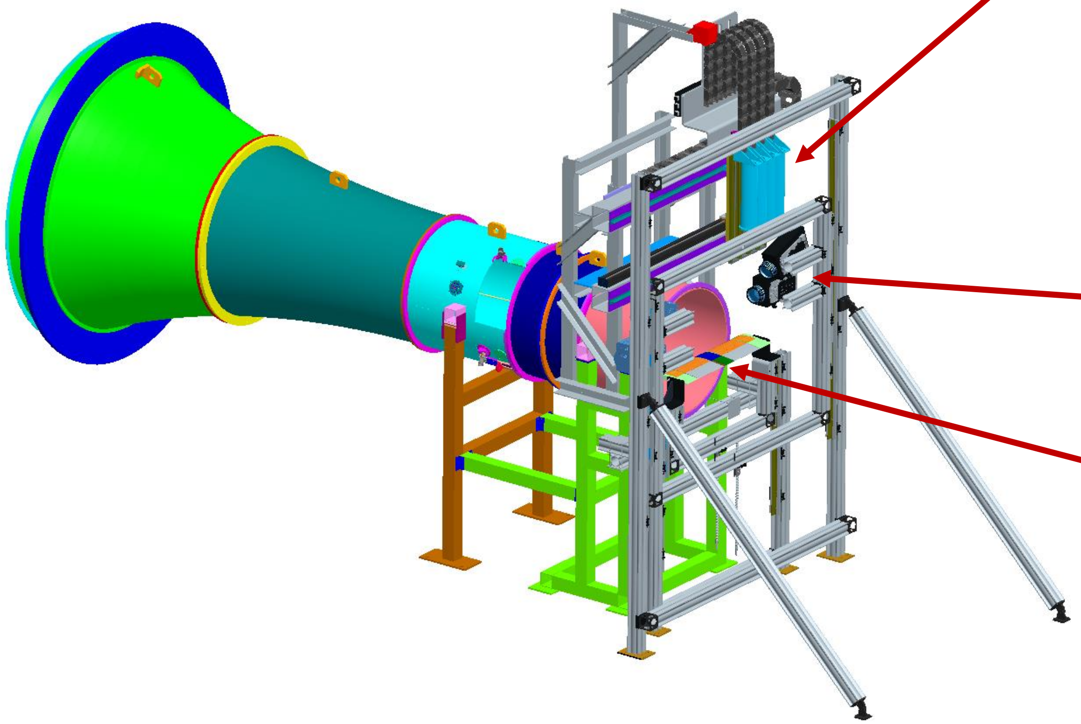
Particle Phase and Temperature

- “Point” measurement at beam waist
- Benchtop success and some success in PSL, with particles moving at 0.5 Mach
- Development continues





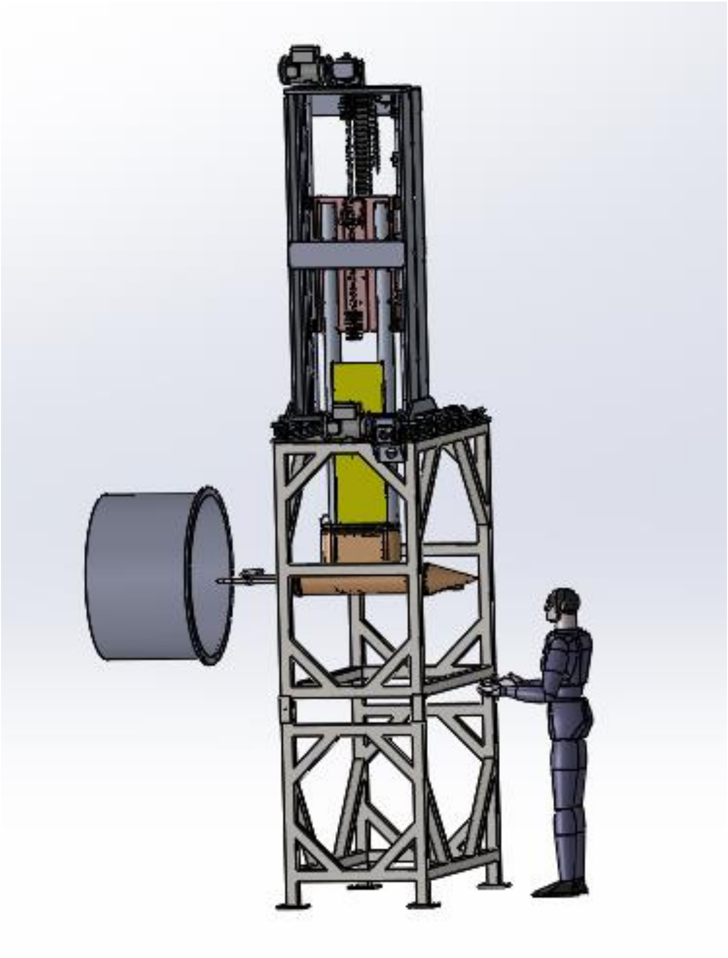
Multi-Probe Traverse System



- Probe traverse
  - Rearward facing total air temperature (TAT) and humidity inlet probe
  - Rosemount/Goodrich TAT
  - SEA Multiwire (MW) probe or interchangeable Ice Crystal Detector (ICD)
- Non-intrusive probe traverse
  - Artium HSI and PDI
- This system includes the ability to translate the airfoil in and out of the flow for the fundamental test.

Planned for Fundamental Test 2 – late 2017

IKP2 Traverse System



- SEA is developing this system for the IKP2
- Traverse Capability:
  - Horizontally (+/- 18” from centerline)
  - Vertically (+22” and -18” from centerline)
- Enable most flight probes such as the particle sizing probes (CDP, CIP, CPI, 2D-S, etc) to be traversable.

Planned for Fundamental Test 2 – late 2017

Traverse Technical Goals

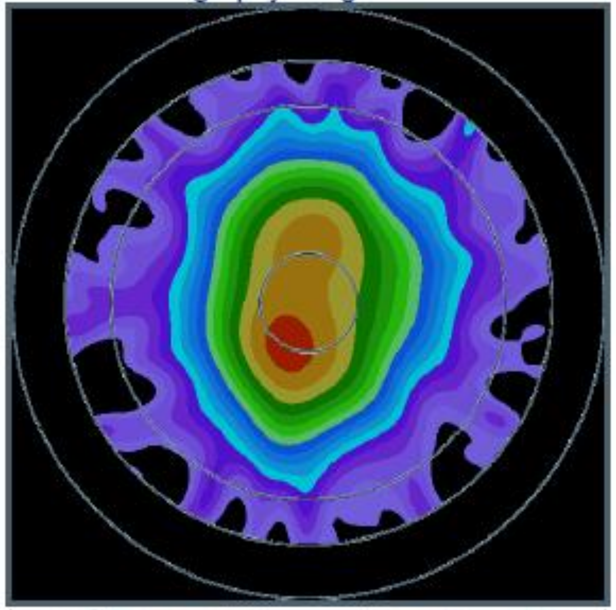
Fundamental Research:

- Determine flow and cloud properties across PSL test section (station 1)
  - Water content (LWC & TWC)
  - Particle size distribution
  - Temperature, humidity
    - Including cloud on / off variation
- Reduce needed test days
  - Minimize need for repeating conditions

PSL General:

- Tomography
  - Verify intensity distribution vs. TWC & PSD
- General facility characterization

Tomography Image of Cloud at PSL



Ice Formation on Airfoil at PSL

NASA ICI Research

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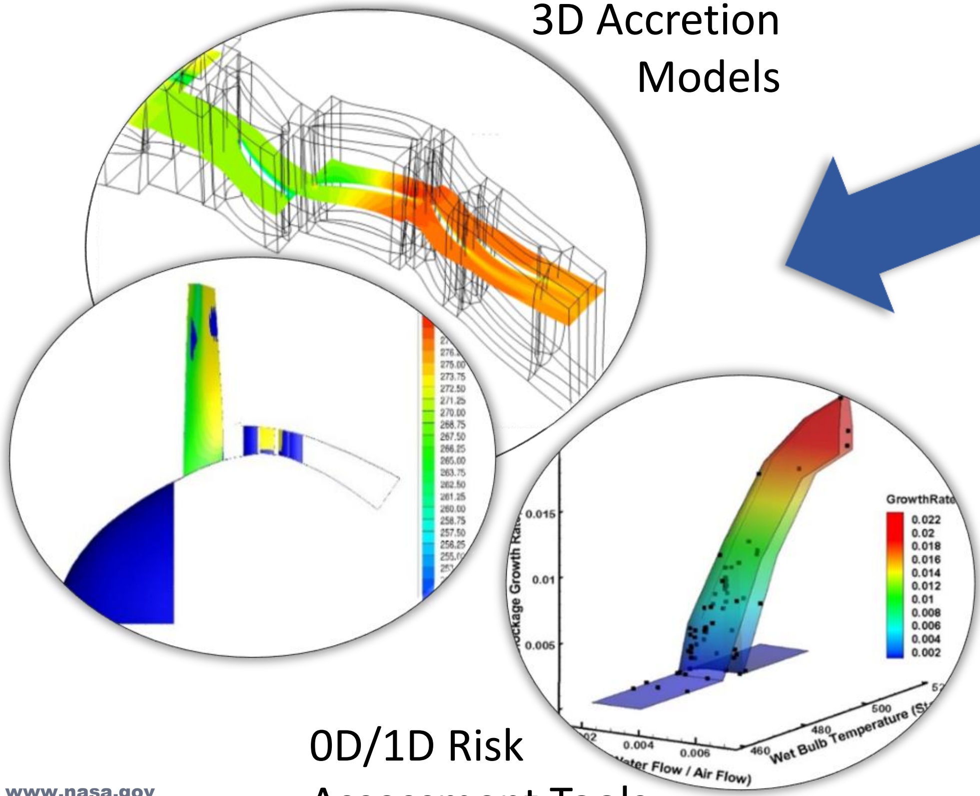
Flight Campaigns

Engine Tests

Fundamental Tests

3D Accretion Models



0D/1D Risk Assessment Tools

Advanced Air Transport Technology Project

Explore and Develop Technologies and Concepts for
Improved Energy Efficiency and Environmental Compatibility for
Fixed Wing Subsonic Transports

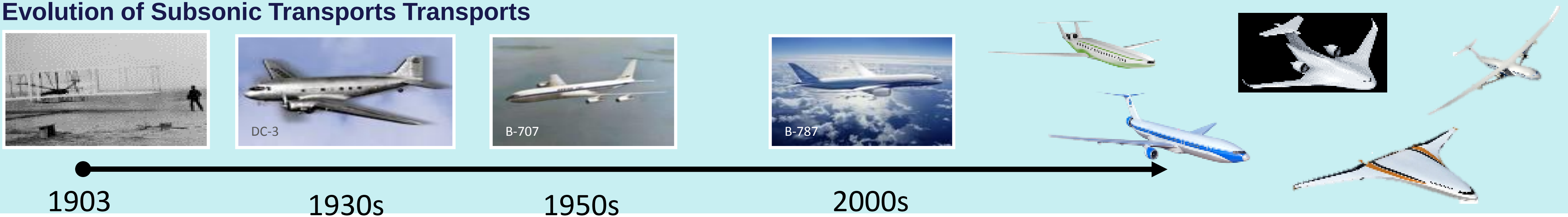
Vision

- Early-stage exploration and initial development of game-changing technology and concepts for fixed wing vehicles and propulsion systems

Scope

- Subsonic commercial transport vehicles (passengers, cargo, dual-use military)
- Technologies and concepts to improve vehicle and propulsion system energy efficiency and environmental compatibility without adversely impacting safety
- Development of tools as enablers for specific technologies and concepts

Evolution of Subsonic Transports Transports



TC 4.3 (FY21): Engine Icing, TRL 2

Objective: Predict likelihood of icing events with 90% probability in current engines operating in ice crystal environments to enable icing susceptibility assessments of advanced ultra-efficient engines (TRL 2)

Description: Develop 0D/1D engine icing computational analysis tool to model the risk/onset of engine icing in current configurations and 3D ice accretion tool to determine the rate of ice growth against experimentally obtained validation data from fundamental and engine/component tests.

Technical Areas and Approaches

Icing Prediction Analysis Tool

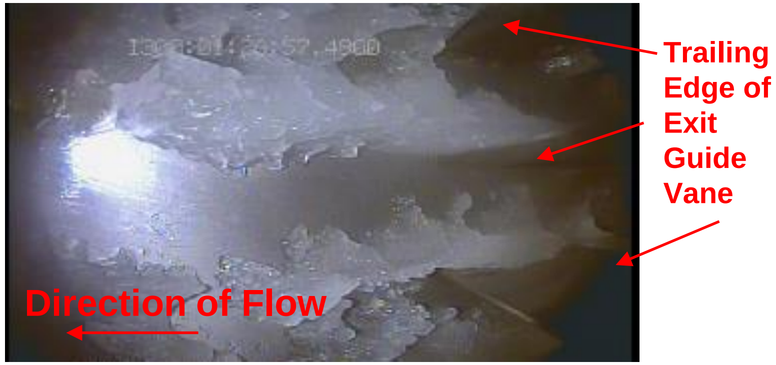
- 0D/1D tool to assess engine conditions conducive to ice formation
- 3D tool to assess rate of ice growth/engine effects

Fundamental Physics and Engine Icing Tests

- Study ice crystal icing in GRC Propulsion Systems Laboratory to validate tools

Benefit/Pay-off

- Enable analysis of ice crystal icing effects on turbofan engines
- Design tools adapted for N+3, compact core, higher bypass ratio turbofan engines to assess icing impacts during development



Ice Formation inside Engine in PSL

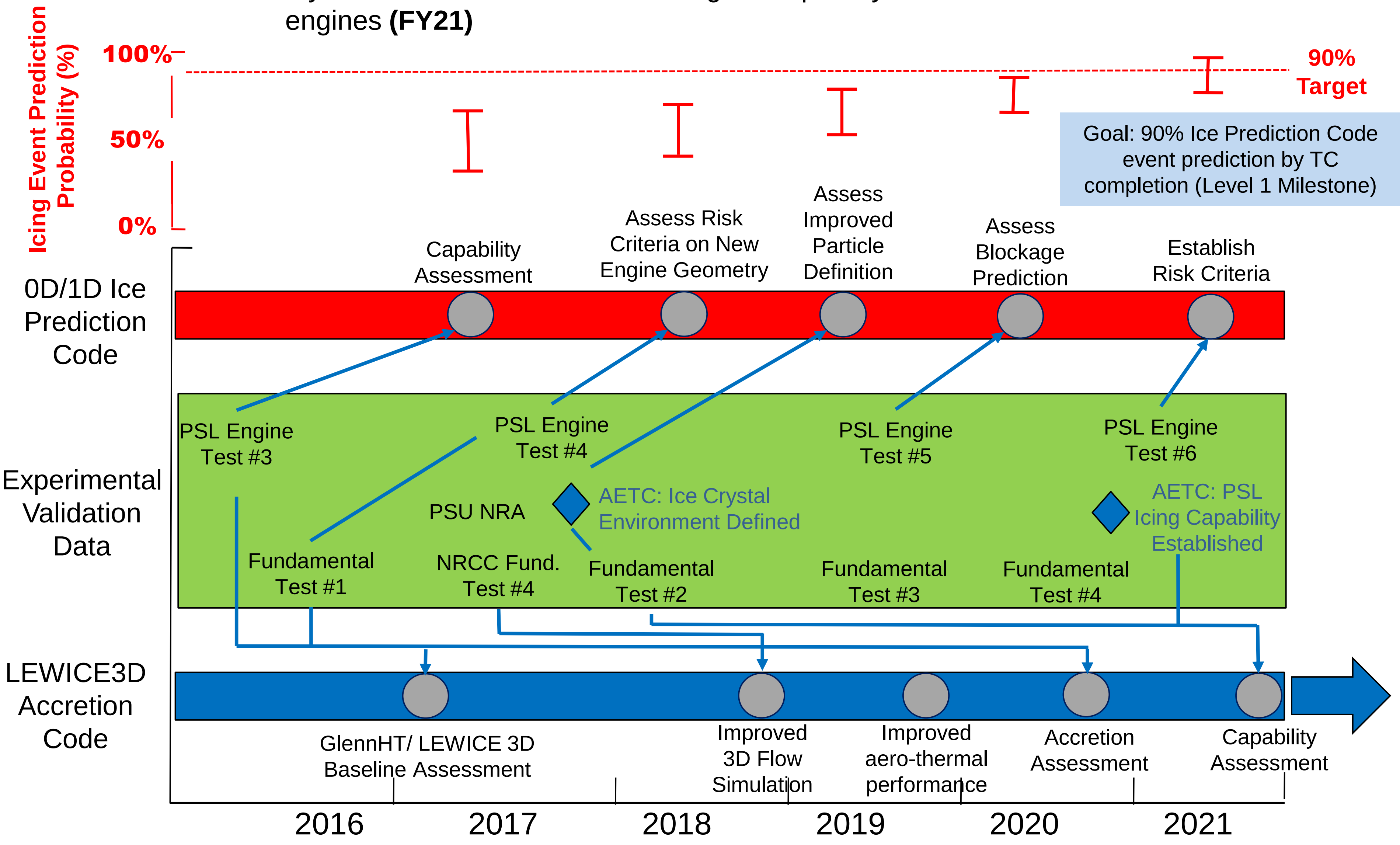
Engine in Propulsion Systems Laboratory for Icing Test

Fundamental Physics Test Ice Accretion

Engine in Ice Crystal Cloud

TC 4.3 (FY21): Engine Icing, TRL 2

Technical Challenge: Predict likelihood of icing events with 90% probability in current engines operating in ice crystal environments to enable icing susceptibility assessments of advanced ultra-efficient engines **(FY21)**



AATT AAI eTC’s

Emerging Technical Challenges to augment engine activities

Emerging Engine Icing Technical Challenge Investments:

4.3.5 Advanced radar for HIWC avoidance/awareness (Real-time capability for detection of HIWC conditions)

- Radar to detect ice crystal environment (not currently available) and environmental characterization data for PSL capability

4.3.6 Engine controls and performance simulation for engine icing mitigation (icing event avoidance through real-time simulation of icing risk through integration with sensors and controls)

0D/1D Modeling

PROBLEM

Develop in-house tool to predict the engine response to ice particle ingestion to evaluate the risk of icing.

OBJECTIVE

Estimate the parameters that indicate the risk of accretion, as well as to estimate the degree of blockage and losses caused by accretion for the ALF502, LF11 engine test points.

APPROACH

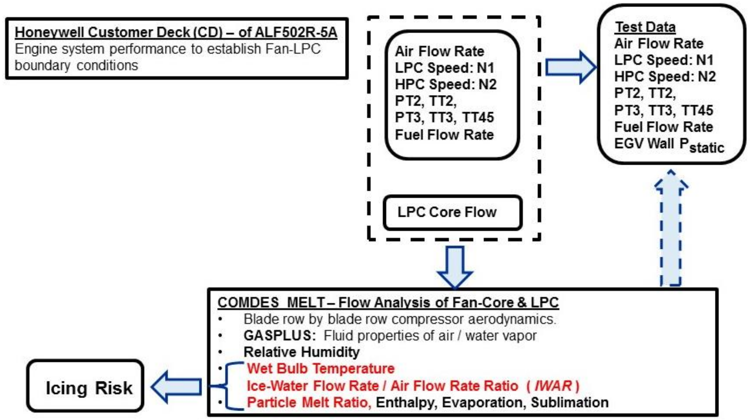
- Mean-line compressor flow analysis code was modified to include the effects of relative humidity on the fluid properties of air and water vapor mixture, and the subsequent effects on compressor performance (mass of water/mass of air) at the engine inlet, as well as the sublimation and evaporation of the particles through the flow path.
- Pre-test evaluation of the LF11 test points using COMES and predict the likelihood of rollback.
- Used code to guide the formulation of the altitude study test points.
- Post-test evaluation of the test points conducted and defined icing risk criteria using COMDES and the engine thermodynamic cycle code.

RESULTS

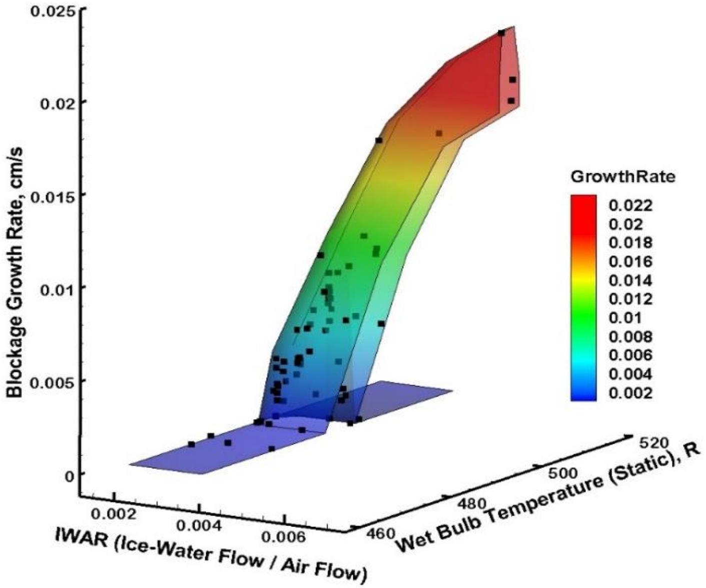
A relationship between blockage growth rate, ice-water flow rate to air flow rate ratio (IWAR), and static wet bulb temperature was observed and plotted generating an "Icing Wedge".

SIGNIFICANCE

- The analysis provided additional validation of the icing risk parameters within the LPC, as well as the creation of models for estimating the rates of blockage growth and losses.
- Enables icing susceptibility assessments of current and advanced ultra-efficient engines.



Computational Process for the flow analysis of the Honeywell engine.

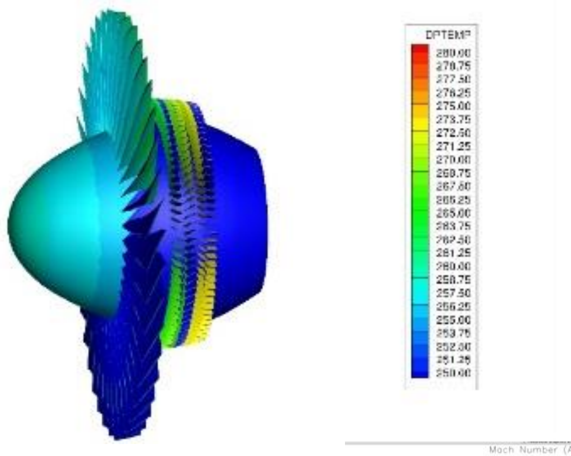


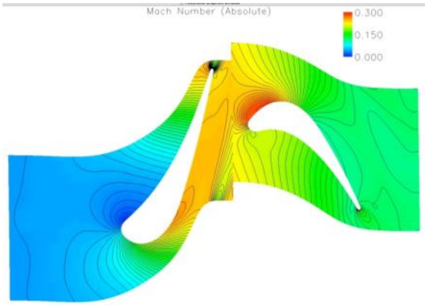
"Icing Wedge" – Risk of Ice Accretion Criteria

POC: Joe Veres and Phil Jorgenson

High Fidelity Engine Icing Simulations

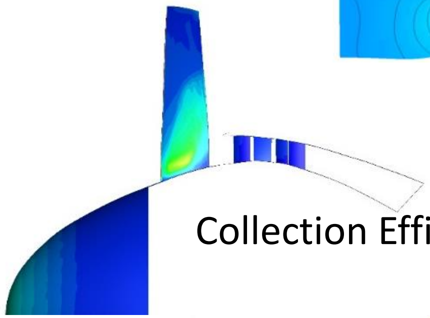
- Goal: Develop a system of codes that can model the performance of an engine and estimate the risk of accretion due to ice crystal ingestion at high altitude and ultimately actual ice accretion.



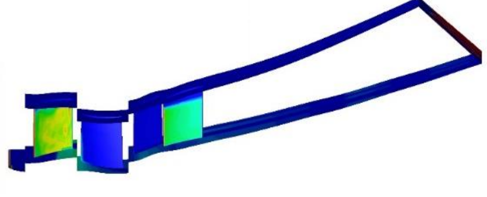


FUTURE DIRECTION:

- Couple Glenn-HT and LEWICE3D simulations more tightly to allc for effect of ice particles on the air flow and include effects of i growth on air flow.
- Inclusion of real gas effects, accounting for humidity and wet bulb temperature
- Modelling of tip clearance region
- Pass heat transfer coefficient distribution to LEWICE3D



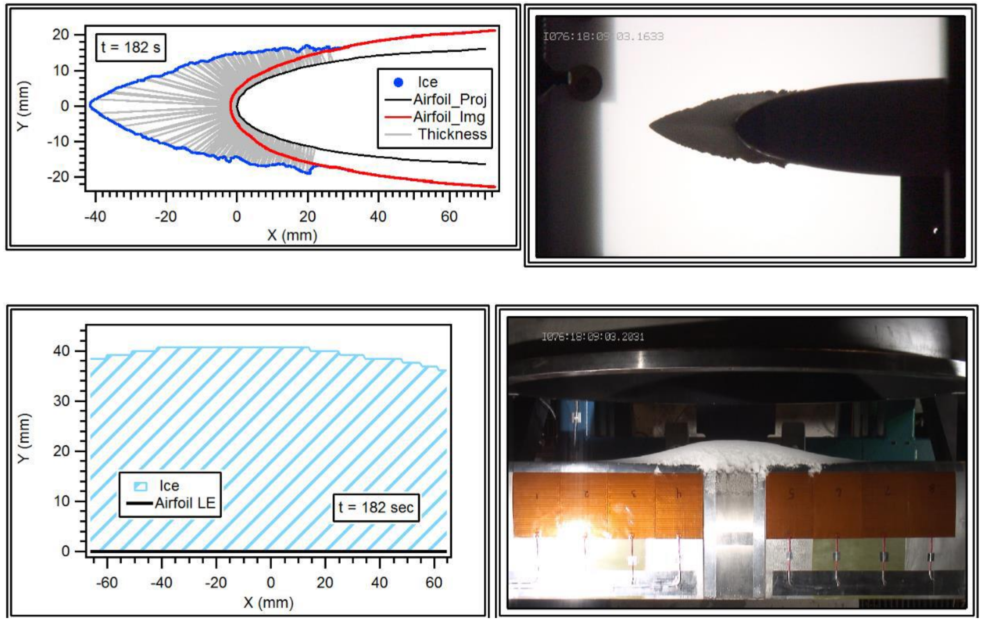
Collection Efficiency on surfaces



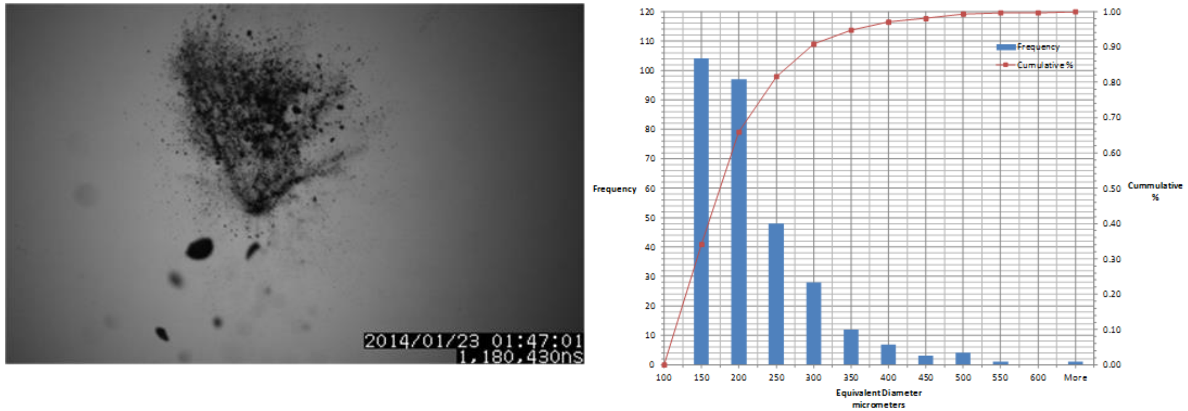
POC: Bill Wright, David Rigby, Ali Ameri, Christopher Porter

Fundamental Testing

- Accretion
  - Investigate the fundamental physical mechanisms of icing that occurs in core compressor regions of jet engines when ingesting ice crystals.
  - Investigate ice on ice erosion
- Particle Impact
  - The effect of target surface temperature and water film thickness, ice particle impact angle and impact velocity (up to 150 m/sec) will be studied parametrically for different melt ratios.



Analysis of ice accretion shapes on a research airfoil located at the test section



Ice Impact and the Fragments Equivalent Diameter Distribution Histogram.

Future Test Plans

- 2017:
  - May: Cloud Calibration
  - August: Fundamental Test at NRC
  - September: Engine Icing Test
  - November: Fundamental Test #2

- 2019:
  - January-June:
    - Cloud Calibration
    - Fundamental Test #3—Working requirements definition right now. Seeking input.
    - TBD Engine Test

- 2020-2021:
  - Fundamental Test #4
  - TBD Engine Test

Potential Engine Tests

- AFRC has available assets.
    - There is a potential to use AFRC spare test assets, for either PSL or flight test
        - Need to explore feasibility
        - Will require funding collaboration

- NASA GRC has two open geometry fan rotors (Rotor 67, R4) available.
    - This would be more of a component level fundamental test.
    - Would need a drive system. Could potentially use the 9x15 system.

- Can seek interest through the RTAPS Contract.

2017 AIAA Aviation Publications

- Paul Tsao: “Preliminary Evaluation of Full Engine Ice Crystal Icing Scaling Application”
- Dave Rigby: “Viscous Three Dimensional Simulation of Flow in an Axial Low Pressure Compressor at Engine Icing Operating Points”
- Pete Struk: “An Initial Study of the Fundamentals of Ice Crystal Icing Physics in the NASA Propulsion Systems Laboratory”
- Tadas Bartkus: “Comparisons of Mixed-Phase Icing Cloud Simulations with Experiments Conducted at the NASA Propulsion Systems Laboratory”
- Michael King: “Particle Size Measurements from the first Fundamentals of Ice Crystal Icing Physics Test in the NASA Propulsion Systems Laboratory”
- Ashlie Flegel: “Ice Crystal Icing Research at NASA Glenn Research Center”