A Systems-Level Perspective on Engine Ice Accretion

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Overview

- Problem of Engine Power Loss
- Modeling Engine Icing Effects
- Simulation of Engine Rollback
- Icing/Engine Control System Interaction
- Detection of Ice Accretion
- Potential Mitigation Strategies
- Future Work

Problem of Engine Power Loss

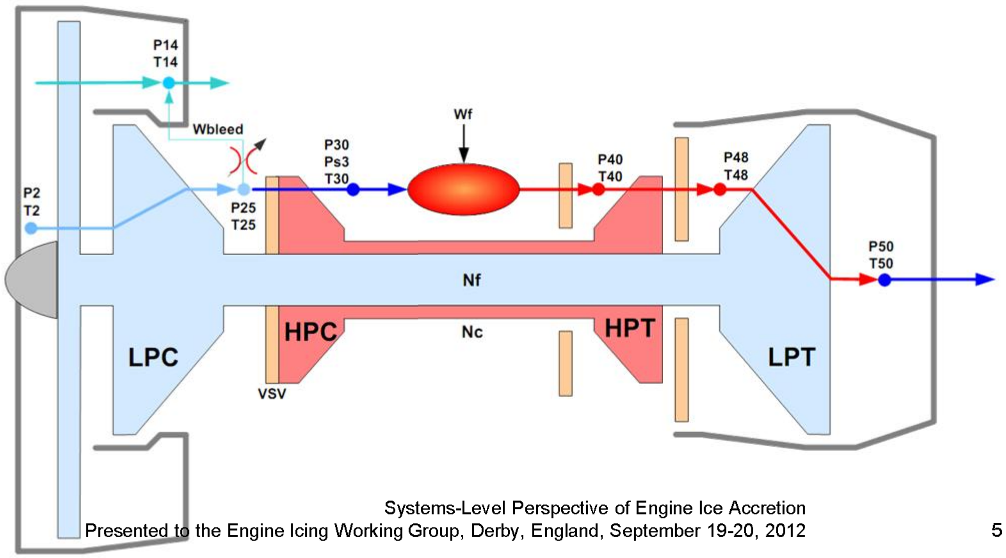
- More than 200 power loss events reported in last 20 years in High Ice Water Content conditions
  - Temporary or sustained power loss, uncontrollability, engine shutdown
- Many possible causes:
  - Compressor surge
  - Flame-out due to combustor ice ingestion
  - Damage due to ice shedding
  - Sensor Icing
  - Engine Rollback

Our Approach

- Accept that ice does accrete in the engine core
- Focus on the impact of the icing on the engine performance
  - Collaborative effort across NASA GRC
    - » Controls and Dynamics Branch
    - » Turbomachinery Branch
    - » Icing Branch
- Develop models to study the conditions in which ice accretes (COMDES+NPSS+GlennICE)
- Use some of these results to develop “simplified” models

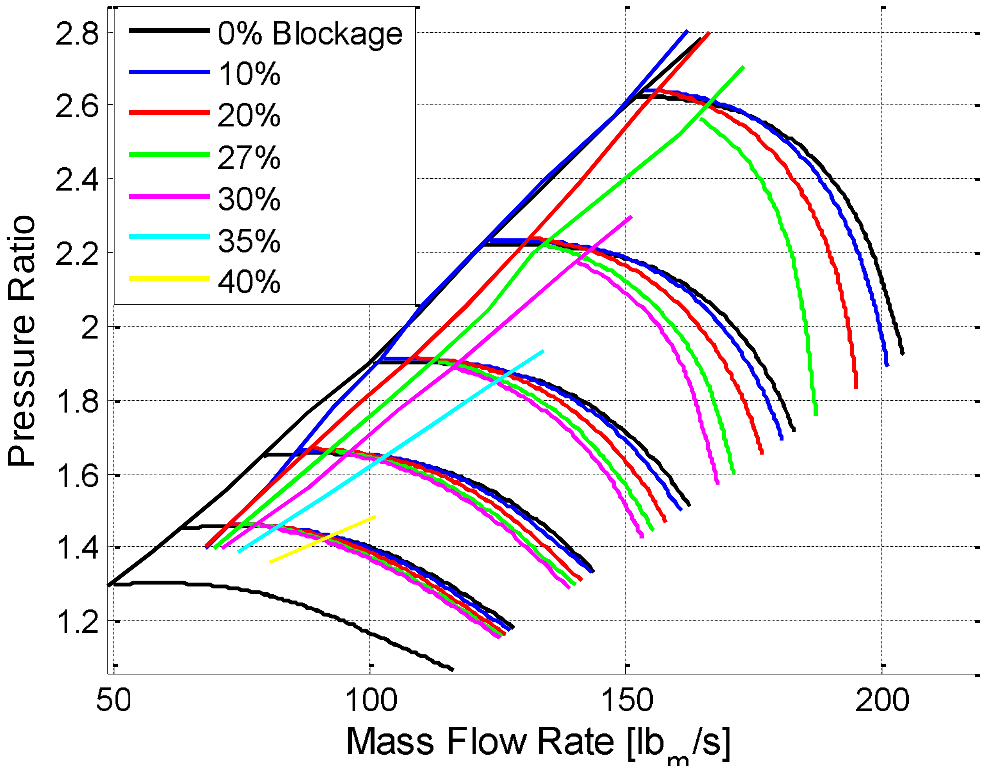
Modeling of Effect of Engine Icing

- C-MAPSS40k engine simulation
  - Commercial 40,000lb_f thrust, high-bypass turbofan engine
  - Physics-based model
  - Realistic engine control system & sensor noise
  - Written in MATLAB/Simulink
  - Modular design
  - Publicly available to US persons



Modeling of Engine Icing Effects

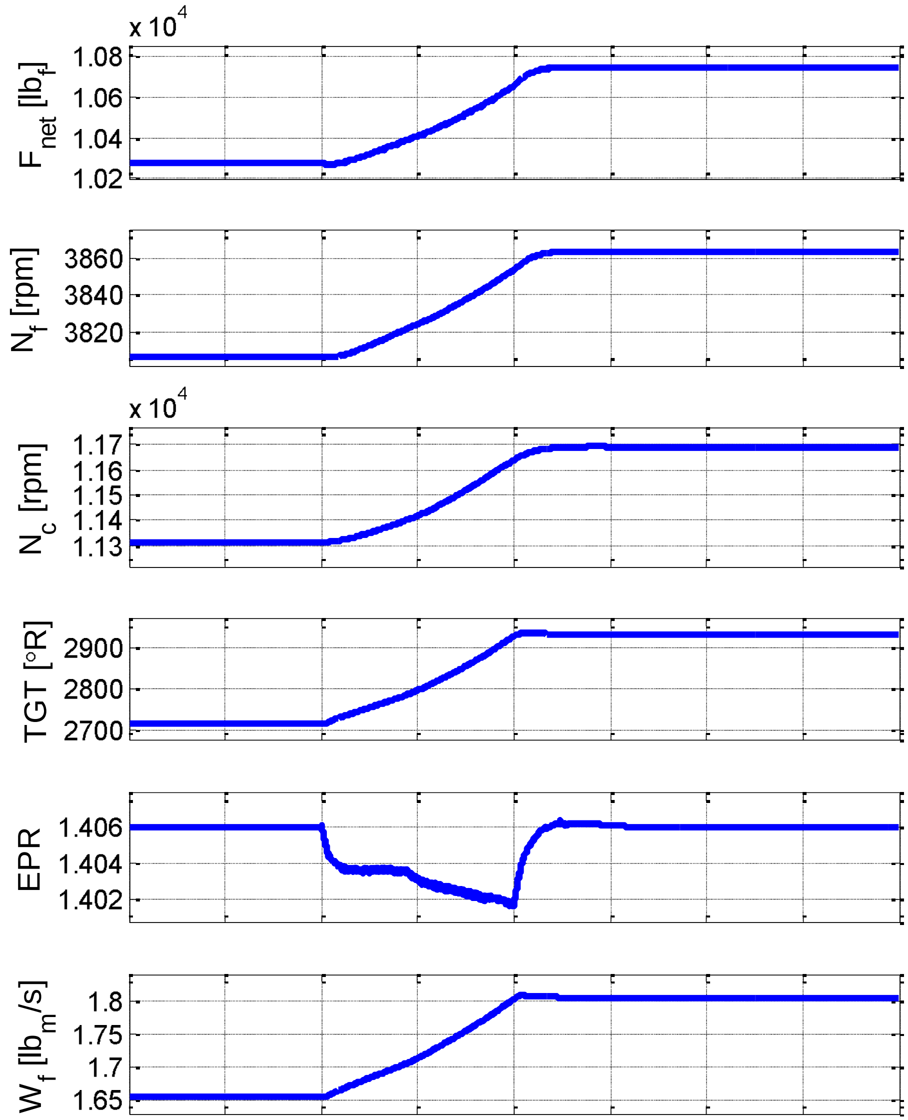
- Low Pressure Compressor (LPC) maps with various quantities of ice blockage in the 2nd row stator
- Integrated into C-MAPSS40k
  - Linear interpolation between maps



Underlying data from:
Jorgenson, P.C.E., Veres, J.P., May, R.D., Wright, W.B., "Engine Icing Modeling and Simulation (Part I): Ice Crystal Accretion on Compression System Components and Modeling its Effects on Engine Performance," 2011-38-0025, SAE International Conference on Aircraft and Engine Icing and Ground Deicing, Chicago, IL, Jun 13-17, 2011. doi:10.4271/2011-38-0025

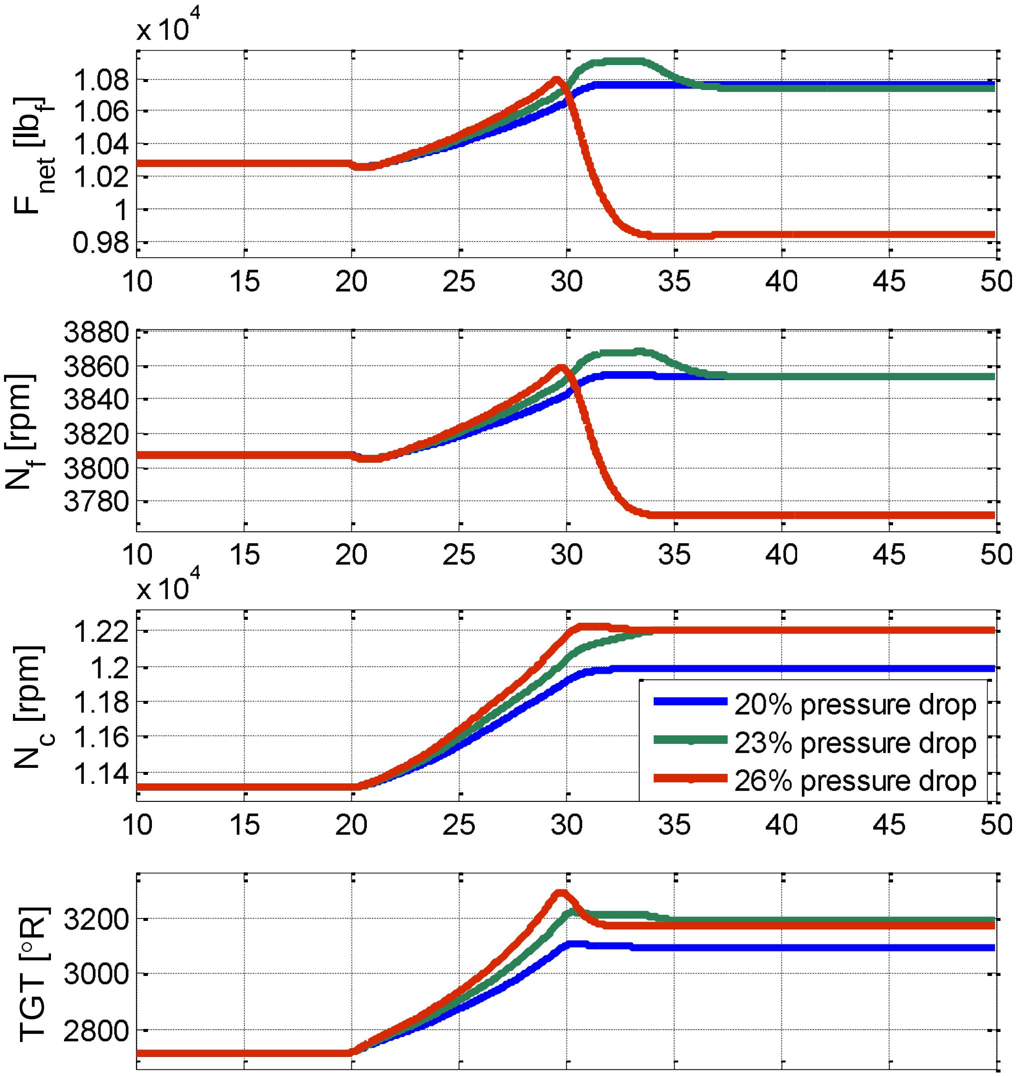
Simulation of Engine Performance during Ice Accretion

- Impact of Engine Icing
  - Start from nominal conditions and increase the blockage level
  - Move from nominal LPC map to 20% blocked map
- Effect:
  - Higher fuel flow rate required to maintain desired setpoint leads to increase in all other parameters
  - No Rollback event



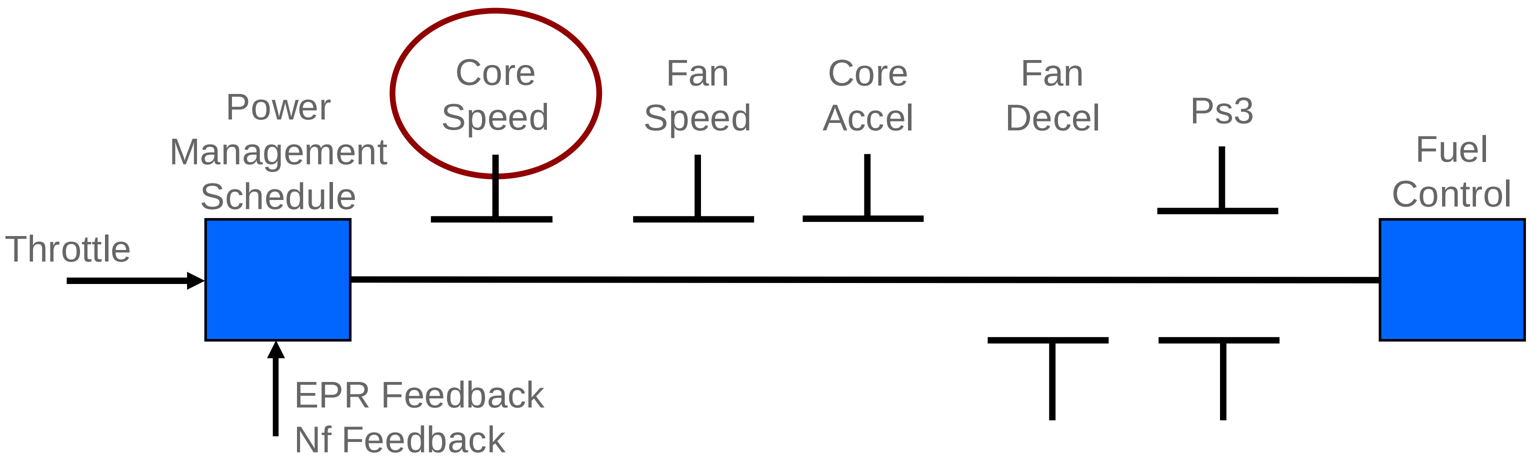
Simulation of Engine Rollback

- As blockage increases, eventually a rollback occurs
- Decrease in thrust
- Decrease in fan speed
- Increase in TGT



Engine Control System

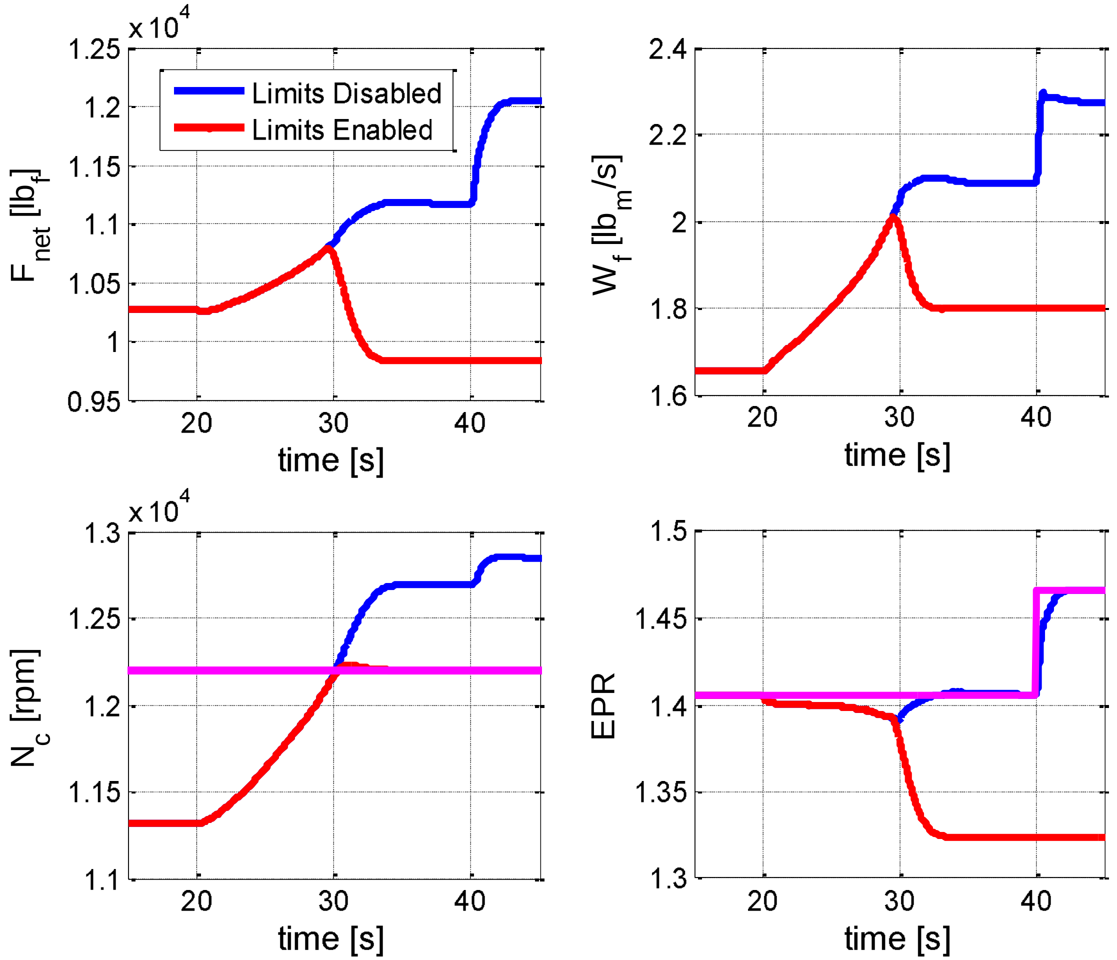
- Power Management
  - Responsible for holding current power level
- Protection Logic
  - Responsible for ensuring safe operation
  - Adjusts Fuel Flow to ensure limits are observed



Controller Response To Icing

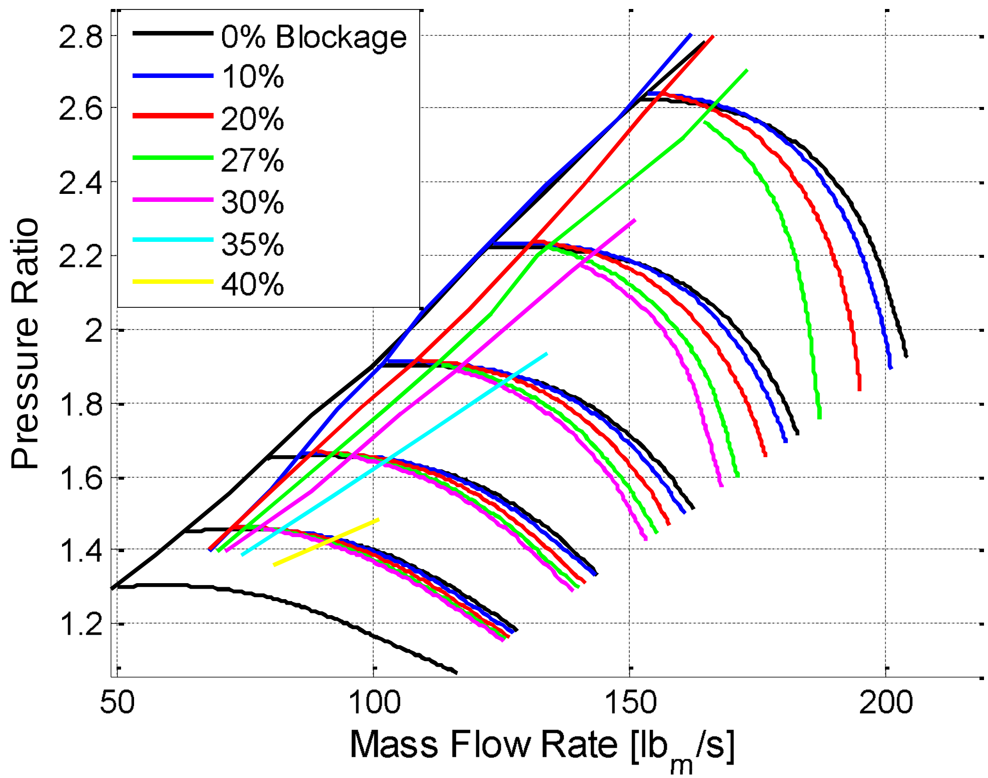
- Core speed limit prevents fuel flow rate from continuing to increase

- Normal operation of controller in the presence of blockage results in rollback



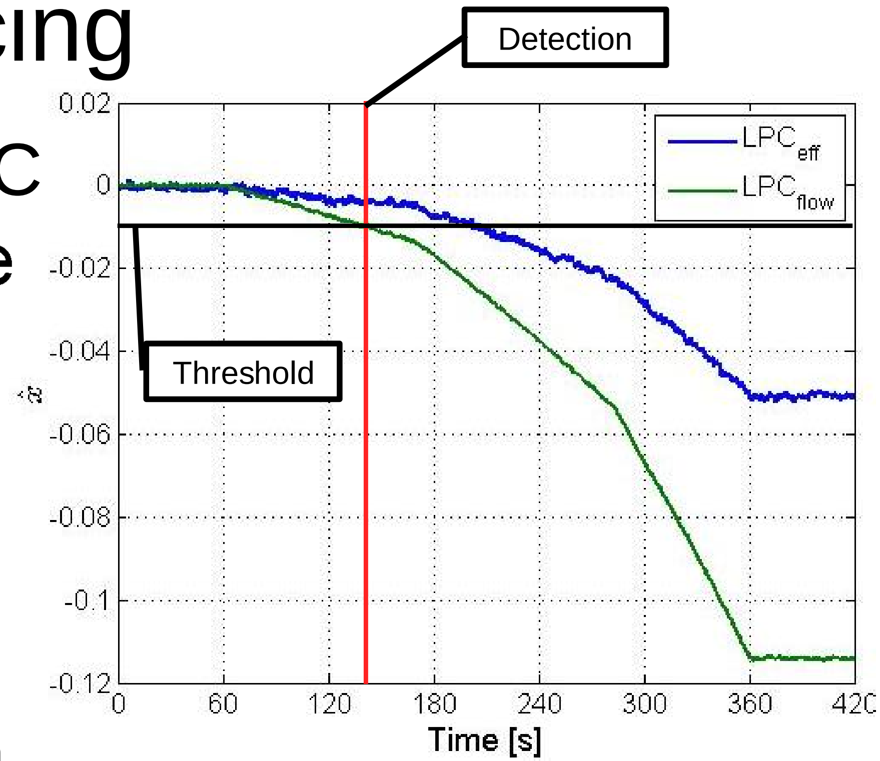
Detection of Engine Icing

- Typically 5 – 7 sensors present in an engine
- Icing causes a change in the LPC operational characteristics
- Operate in conjunction with airframe devices to reduce chance of false-positive



Detection of Engine Icing

- Estimate the change in LPC "health" based on available sensors and look for a decrease in the flow capacity
- Linear estimator approach
  - Uses simple 1D interpolation
  - Low memory usage
  - Should be capable of operating real-time in typical FADEC



- Early Results:
  - False-Positive = 0.2%
  - True-Positive = 99.6%
  - Average Blockage Level at Detection = 4.55%

Mitigation of Engine Icing

- Ideally, completely avoid ice accretion
- If we can detect accretion can the engine controller act to mitigate the impact of the ice blockage?
- Potential mitigation strategies:
  - Operate actuators off-nominally to change operating point
    - » Close inter-compressor bleed valve or move HPC inlet guide vanes off schedule
  - Use existing airframe integration in novel ways
    - » Power take-off, Customer air bleed
  - Change shaft speed to cause ice to shed
- All of these approaches require iteration with an icing code to determine the effect of the new condition on ice accretion!

Future Plans

- Upcoming testing at NASA Glenn's Propulsion System Laboratory promises to provide validation of models and detection algorithm
- Develop mitigation strategies – iterate with the NASA GRC icing code to determine how the change in operating point impacts the accretion of ice & possible testing in PSL

Acknowledgements

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References

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Detection of Engine Icing

- Linear estimator – optimal unbiased least squares

$$y = Hx$$

$$\hat{x} = (H' R^{-1} H)^{-1} H' R^{-1} y$$

- Detection threshold can be chosen to obtain a desired false-positive rate
- As threshold increases the detection latency also increases