



Flight Test of a Resistive Heating Coating for Visualizing Flow Transition

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Outline



- Objectives/Motivation
- Boundary Layer Transition Detection
- ReHEAT Technique
- Initial Wind Tunnel Testing
- Flight Testing
- Results
- Conclusions/Future Work

Objectives/Motivation



- Reducing drag on aerospace vehicles critical to increasing fuel efficiency and reducing pollution
 - One method is to keep the boundary layer over a wing laminar for as long as possible (delay transition to turbulent)
- Determining transition location
 - Identifying change in heat transfer to the surface caused by laminar or turbulent flow
 - Multielement hot-film sensors (point-based)
 - Sublimating chemicals
 - IR thermography/Temperature Sensitive Paint (TSP)
- Testing in cryogenic facilities
 - Can provide “flight” Reynolds number conditions – critical for natural laminar flow (NLF)
 - Develop/deploy a technique that can visualize the change in heat transfer
 - Increase testing efficiency for transition location studies
- Extend this to flight testing

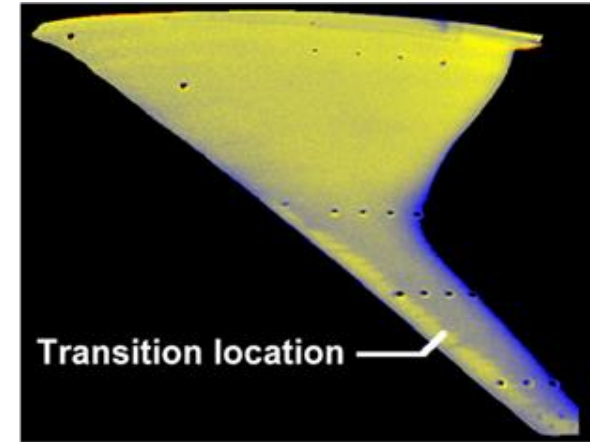
Transition Detection



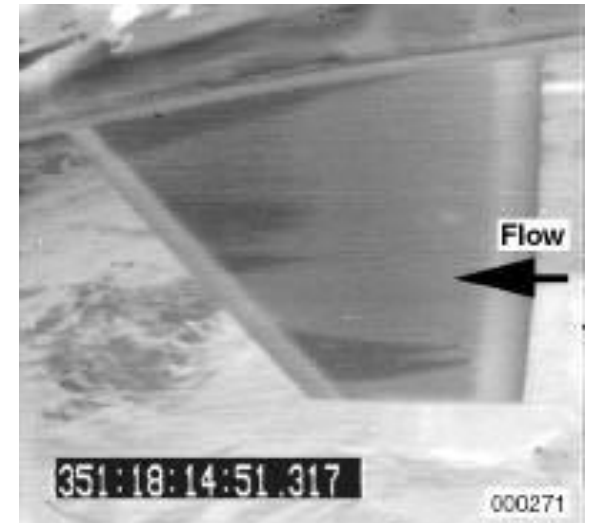
- IR thermography and TSP are ideal for this
 - Employed in several facilities and flight tests
 - Can detect natural transition (no augmentation of signal required)
 - TSP is typically suitable in conditions that IR thermography is not (e.g. cryogenic facilities)
- Transition Detection can have several caveats
 - Natural transition causes small temperature changes (usually 0.1 K or less)
 - Can be difficult to distinguish from other temperature sources (friction, model heating, etc.)
- Usually increase the magnitude of heating by applying a rapid temperature step
 - Usually accomplished by a rapid injection of N_2 or rapid decrease in the injection of N_2
 - Can require several minutes to cycle a data point
 - Can require alteration of the flight profile
 - Heating the surface with the sun
 - Rapid changes in altitude

Wind tunnel testing

Flight Testing



Transition detection using TSP at NTF

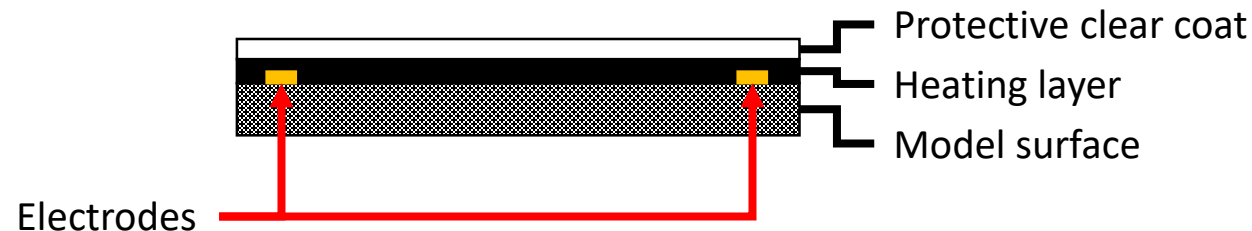


Transition detection using IR at
supersonic flight speeds

ReHEAT Technique



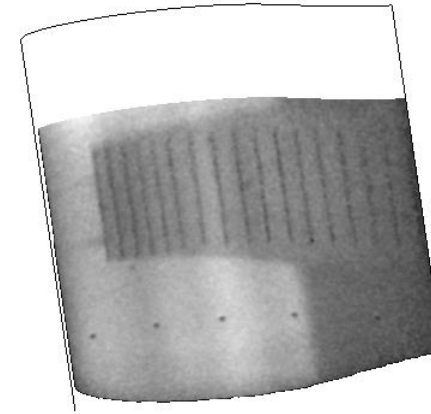
- Alternative method to introducing a temperature step
 - Originally introduced by Klein, et al. (2015)
 - Involves painting a conductive layer to the model surface
 - Apply current to the layer and it heats up (like an electric blanket)
 - Temperature step is applied to the model, not the airflow
 - Wind tunnel – potential savings in time and consumables
 - Flight testing – potentially less modifications of flight techniques needed to heat model
- **Resistive**
 - **Heating for the**
 - **Evaluation of**
 - **Aerodynamic**
 - **Transition**



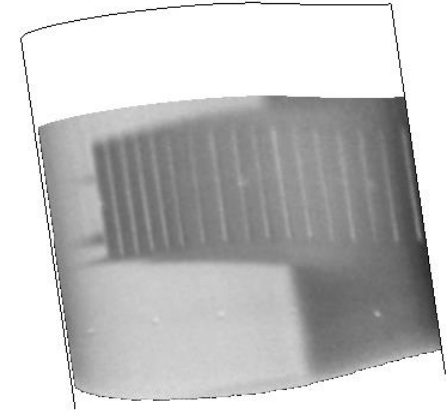
Initial Wind Tunnel Testing



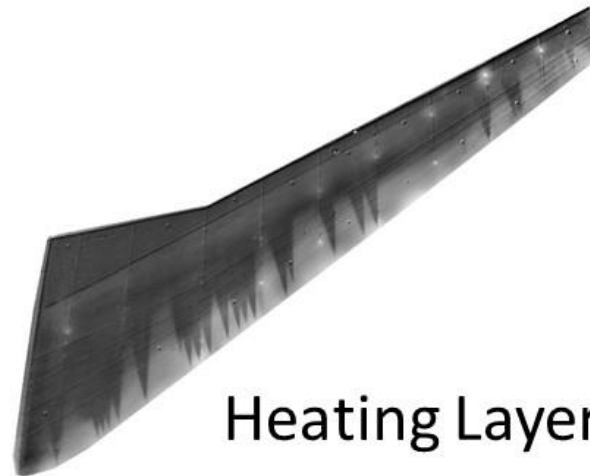
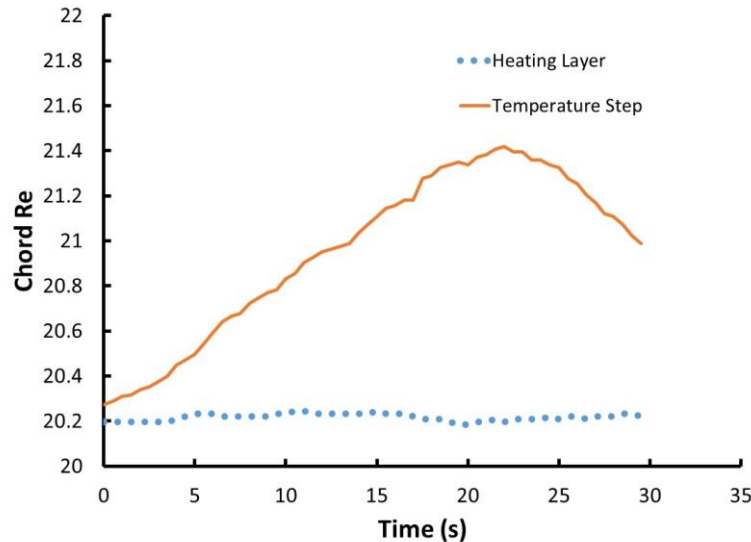
- Conducted at the 0.3-m Transonic Cryogenic Tunnel and NTF
- Laboratory testing conducted down to liquid N₂ temperatures (77K, -320 °F)
 - No loss of structural integrity
 - Heating layer still functioned
- Applied to an NLF airfoil (0.3-m TCT) and CRM-NLF concept
 - Tested down to 110K (-262 °F)
 - Compared with a standard N₂ temperature step



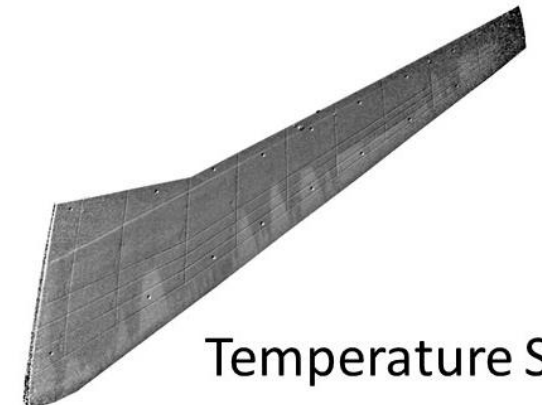
*TSP/Heating layer
Coating*



*Traditional
temperature step*



Heating Layer

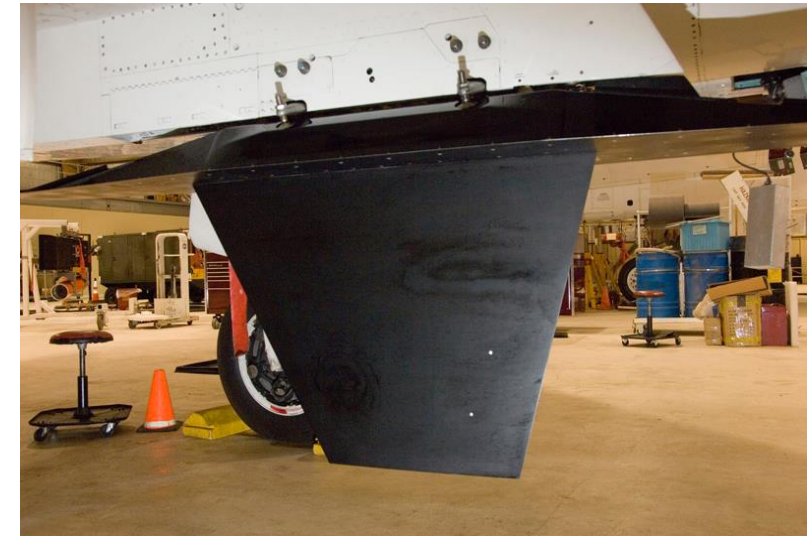
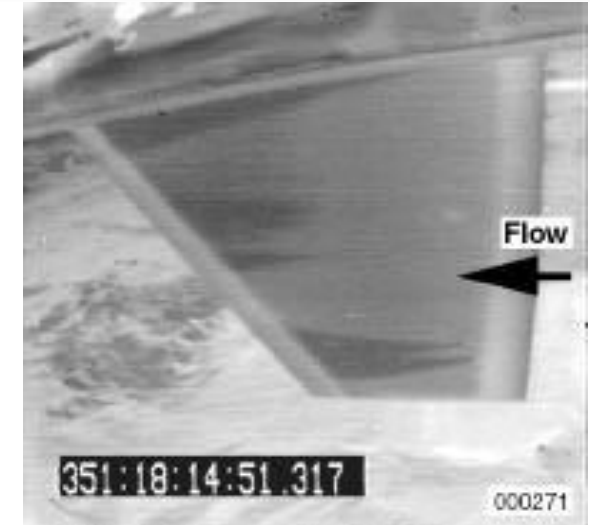


Temperature Step

Extending ReHEAT to Flight Testing



- Desired for upcoming flight testing program
 - Cross-flow Attenuated Natural Laminar Flow (CATNLF) concept
- Initial flights on a “Shark Fin” model*
 - Tested in late 1990s at supersonic speeds (F-15B)
 - Aluminum model encased in fiberglass
 - Data acquired using an IR camera mounted in a pod under the wing
- Flights conducted at subsonic speeds at various altitudes (for Reynolds number testing)



*Details in van Dam *et al.*, In-Flight Visualization of Supersonic Flow Transition Using Infrared Imaging,” *J. Aircraft*, Vol. 39, No. 6, 2002, pp. 936-944

Shark Fin mounted on F-15B

Initial Considerations for Flight Testing with ReHEAT



- Available power
 - Wind tunnel testing employed laboratory power supplies
 - Up to 600 V, 1500 W
 - F-15B limited to 100 V
 - This determines the resistance requirements for the coating
- ReHEAT application requirements
 - Initial model surface is fiberglass (no insulating layer required)
 - Electrode placement to get most heating on imaged surface
 - Need to protect personnel and coating during installation
 - Employed clear coat protective layer
- Surface finish
 - Need to be smooth for transition experiments

Application of ReHEAT to Model



Apply Clearcoat and polish

Final ReHEAT Layer Characteristics



- Final finish measured with roughness gage
 - About $0.05\text{ }\mu\text{m}$ ($2\text{ }\mu\text{-inch}$)
 - Measured in several places, but not on leading edge
- Electrical characteristics
 - Resistance of entire layer $\sim 15\text{ }\Omega$
 - Ground tested with 150W power



Flight Test Parameters



- IR imaging collected during two flights of F-15B
- Altitude ranged from 1524 m (5000 ft) to 15,087 m (49,500 ft)
 - Different Reynold number conditions
- All images collected at subsonic speed ($M=0.85$)
- Several different heating routines tested
 - Using RTDs to try and control heating
 - Heating for a certain amount of time
 - All power applied was 100 VAC, 400 Hz



ReHEAT Coated
Test Article

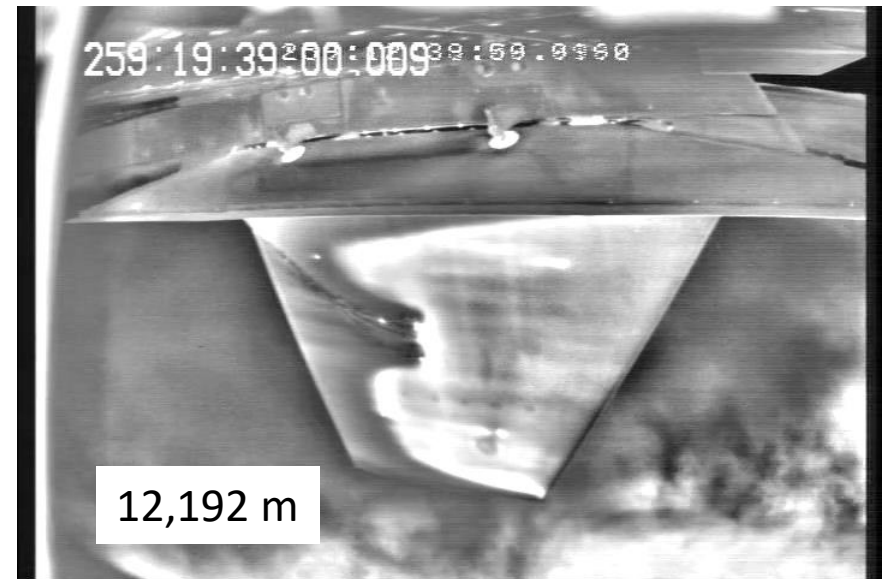
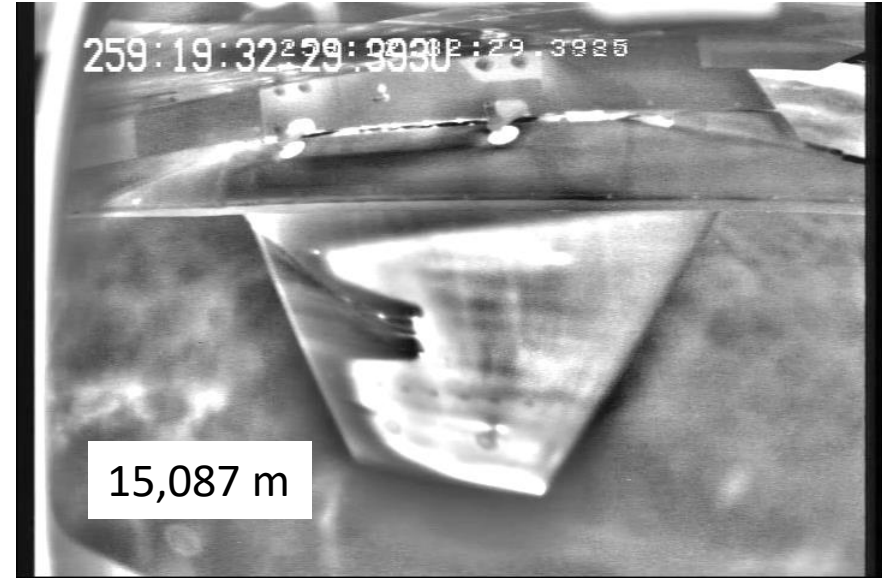
Flight 1	Flight 2
1524 m (5000 ft)	8839 m (29,000 ft)
6096 m (20,000 ft)	3657 m (12,000 ft)
15,087 m (49,500 ft)	1524 m (5000 ft)
12,192 m (40,000 ft)	

Results from Higher Altitudes



- 15,087m (49,500 ft) and 12,192 m (40,000 ft)
- Lower Reynolds number conditions
- Laminar flow is lighter regions
- Turbulent flow is darker
- Conditions do not warrant ReHEAT

ReHeAT ON

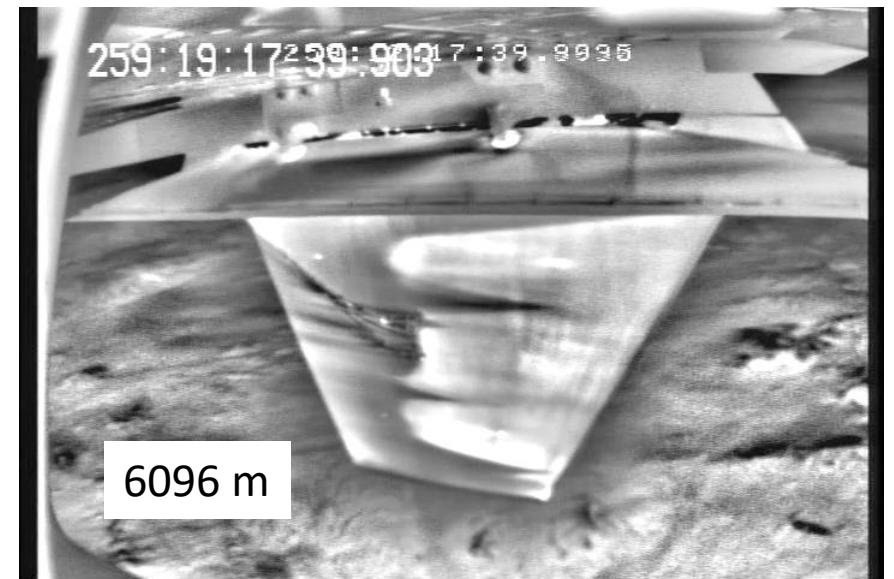
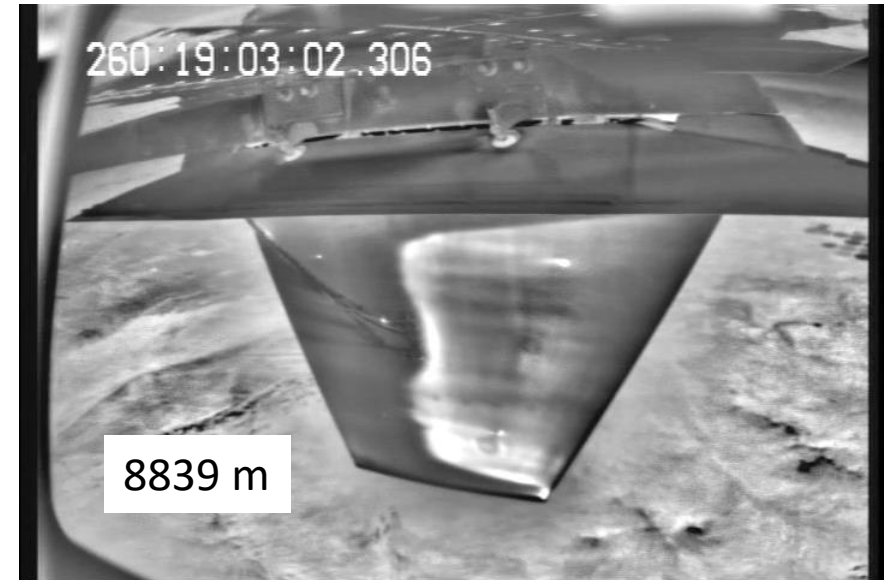


Results from Middle Altitudes



- 8839 m (29,000 ft) and 6096 m (20,000 ft)
- Higher Reynolds number conditions
- ReHEAT greatly enhances contrast between laminar flow and turbulent flow
- Higher Reynolds number conditions
 - Temperature difference between laminar and turbulent flow is smaller

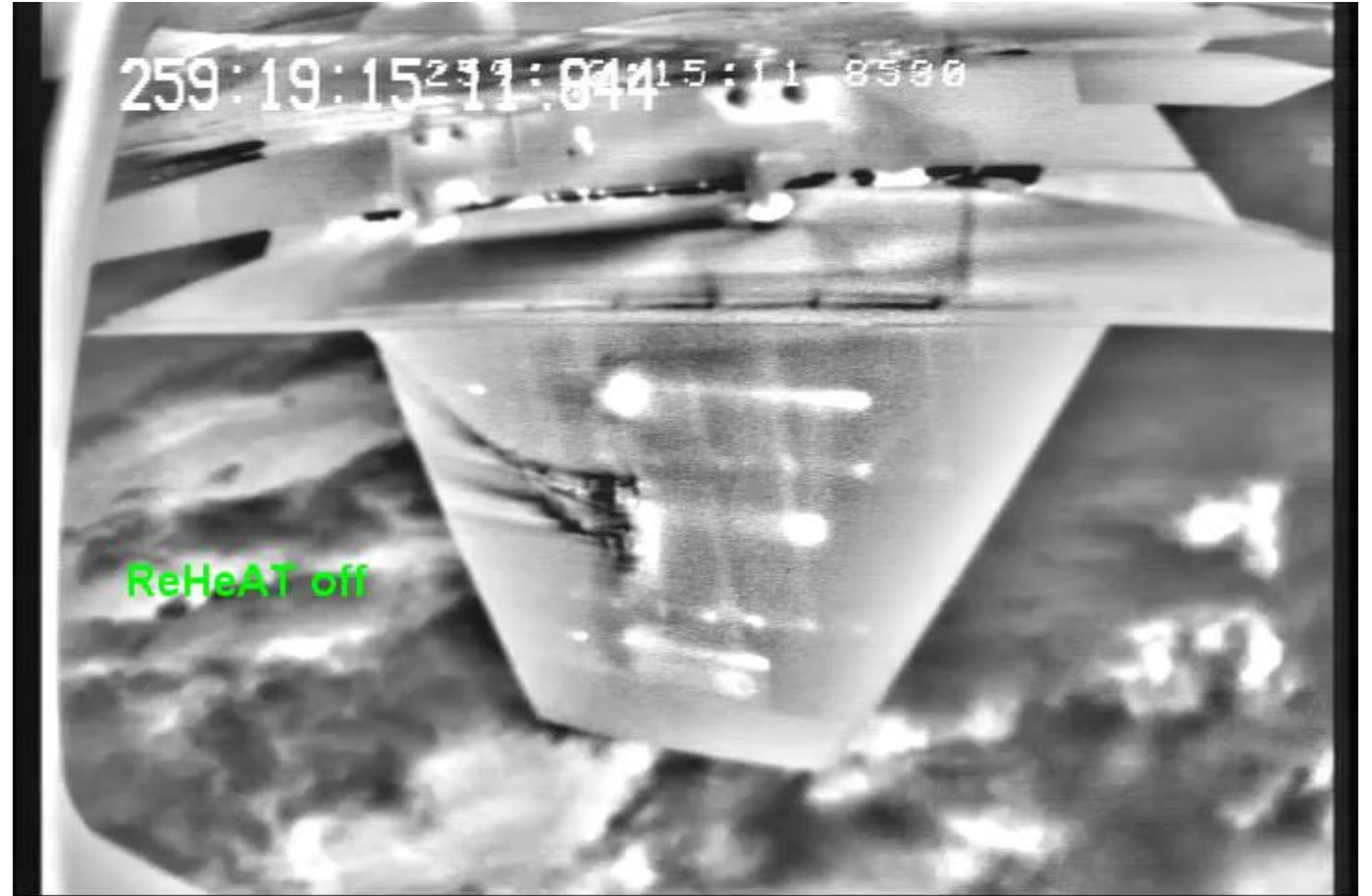
ReHeAT ON



Effects of ReHEAT



- 8839 m (29,000 ft)
- About 90 seconds of flight

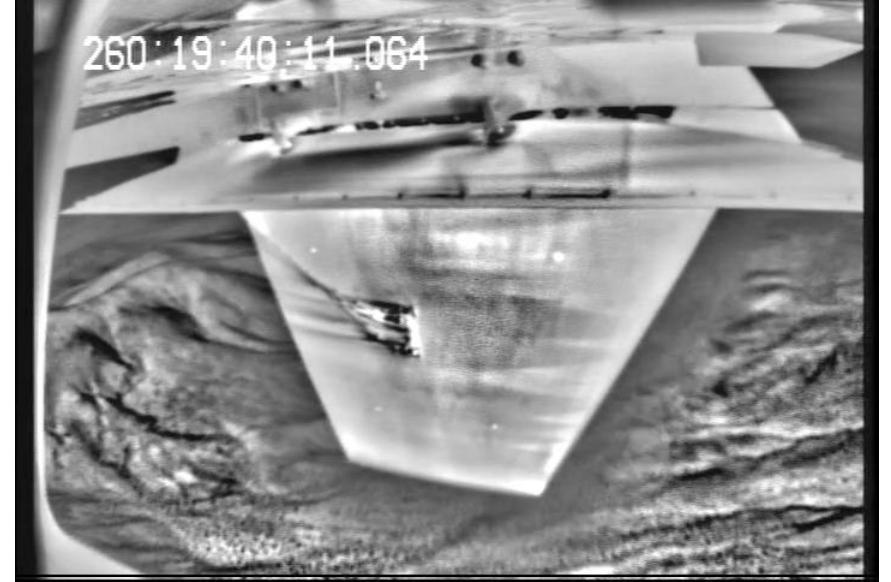


Results from Lowest Altitude



- 1524 m (5000 ft)
- Highest Reynolds number condition
- ReHEAT enhances contrast significantly
 - Still not great contrast
- Highest Reynolds number conditions
 - Temperature difference between laminar and turbulent flow is very low

ReHeAT ON



Enhancing Contrast



- Multiple strategies
- First ratio an image before ReHEAT powered and after
- Use a Contrast Limited Adaptive Histogram Equalization (CLAHE) routine
 - Capable of equalizing a histogram locally
 - Especially good for images that have large regions with small contrast changes
 - Similar to routines used by Ted Garbeff for IR thermography



After CLAHE applied

Surface Roughness



- During flight, relatively large amounts of bypass transition were seen
 - Manifest as “turbulent wedges”
 - Usually caused by surface roughness/defects
- Roughness measurements in these locations show local roughness increased by up to 40
- Clear coat was reapplied and repolished for future flights



Orange Peel (3)

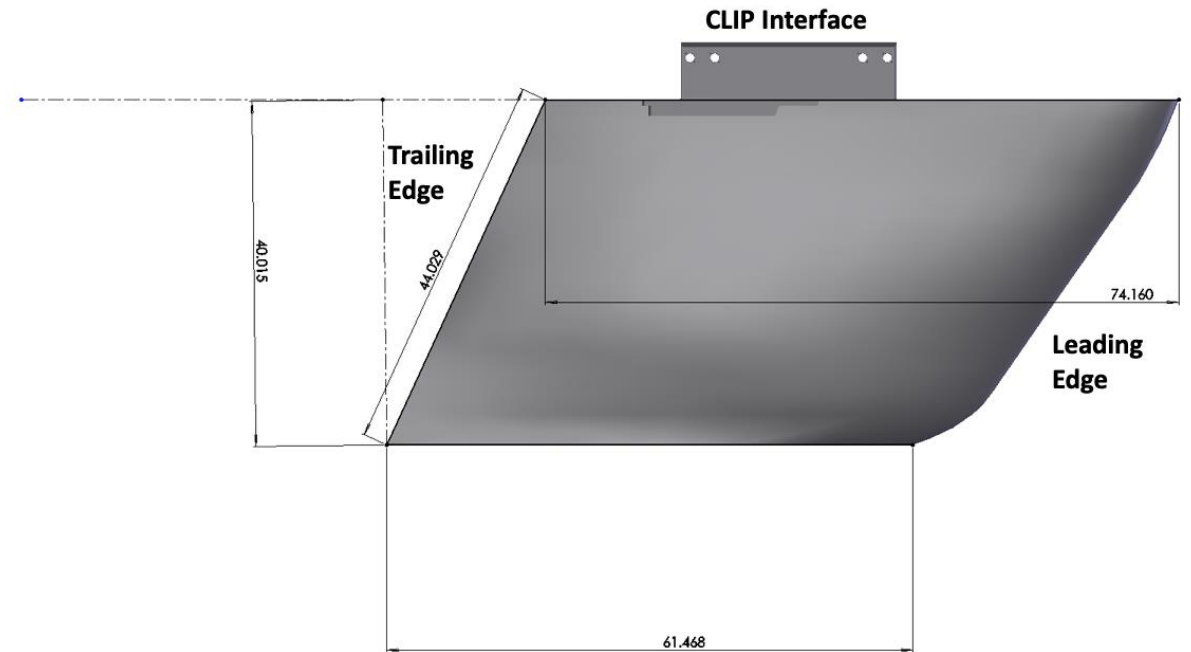


Potential Damage (2)

Summary/Future Work



- ReHEAT technology can be applied to flight testing
- For cases where the temperature difference between laminar and turbulent flow is small, ReHEAT can enhance contrast
- Future flights need to address surface roughness issues
 - Next flights will explore the ability to re-polish surface to restore original finish
 - Explore alternative ways to strengthen the clear coat exterior
- Improvements made for upcoming laminar flow flight testing
 - CATNLF concept
 - Model designed and currently being fabricated



CATNLF Model

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