



## Space Shuttle Boundary Layer Transition Flight Experiment Overview

Karen T. Berger

NASA Langley Research Center, Hampton, VA

Brian P. Anderson, Charles H. Campbell, Michael T. Garske  
NASA Johnson Space Center, Houston, TX

Gerald R. Kinder

The Boeing Company, Huntington Beach, CA

Ann Micklos

United Space Alliance, NASA Kennedy Space Center, FL

Presented By

**Karen Berger**

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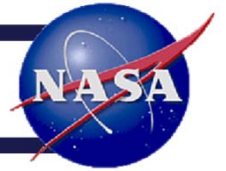
Jet Propulsion Laboratory

Pasadena, CA





# Outline



- Introduction and Motivation
- Design Overview
- Review of Previous Flights
- STS-134 Flight Data & Observations
- Summary



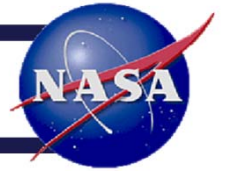
# Introduction and Motivation



- Damage Assessment Team (DAT) established following *Columbia* accident
- Boundary Layer Transition Tool developed
- Two tile gap fillers observed protruding during STS-114 inspection
- BLT prediction uncertainty risks higher than spacewalk risks - repair spacewalk completed
- Protuberance flight test purposefully tripping boundary layer recommended and approved by Space Shuttle Program following STS-114.
- Proposed for all three vehicles but initially only approved for *Discovery*; *Endeavour* approved later



# Design Overview: Protuberance



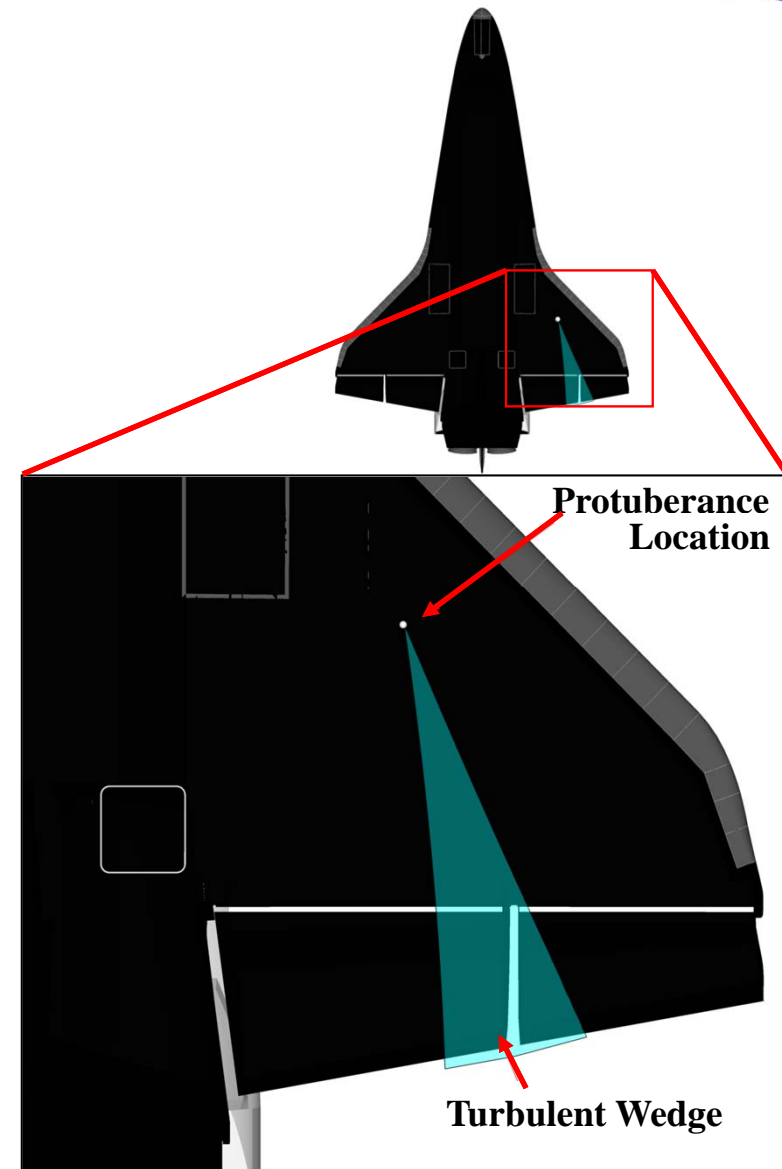
- Incremental approach to flight test for safety
- Protuberance height derived with RTF BLT tool
  - $Re_\theta/M_e$  correlation using best estimate coefficient
  - First flight: 0.25 inches (~Mach 15)
  - Second/Third flights: 0.35 inches (~Mach 18)
  - Fourth/Fifth flights: 0.50 inches (~Mach 19.2)



# Design Overview: Placement



- Top design constraint for flight experiment was safety
- Region of turbulent flow (aka, turbulent “wedge”) downstream of surface disturbance causing boundary layer transition
- Protuberance placement based on:
  - Instrumentation channels/wiring
  - Ascent debris: some areas less prone to damage
  - TPS/Structural margins: turbulent wedge heating can reduce TPS/structural capabilities
- Analysis results showed risk of critical damage within wedge < 1:10,000



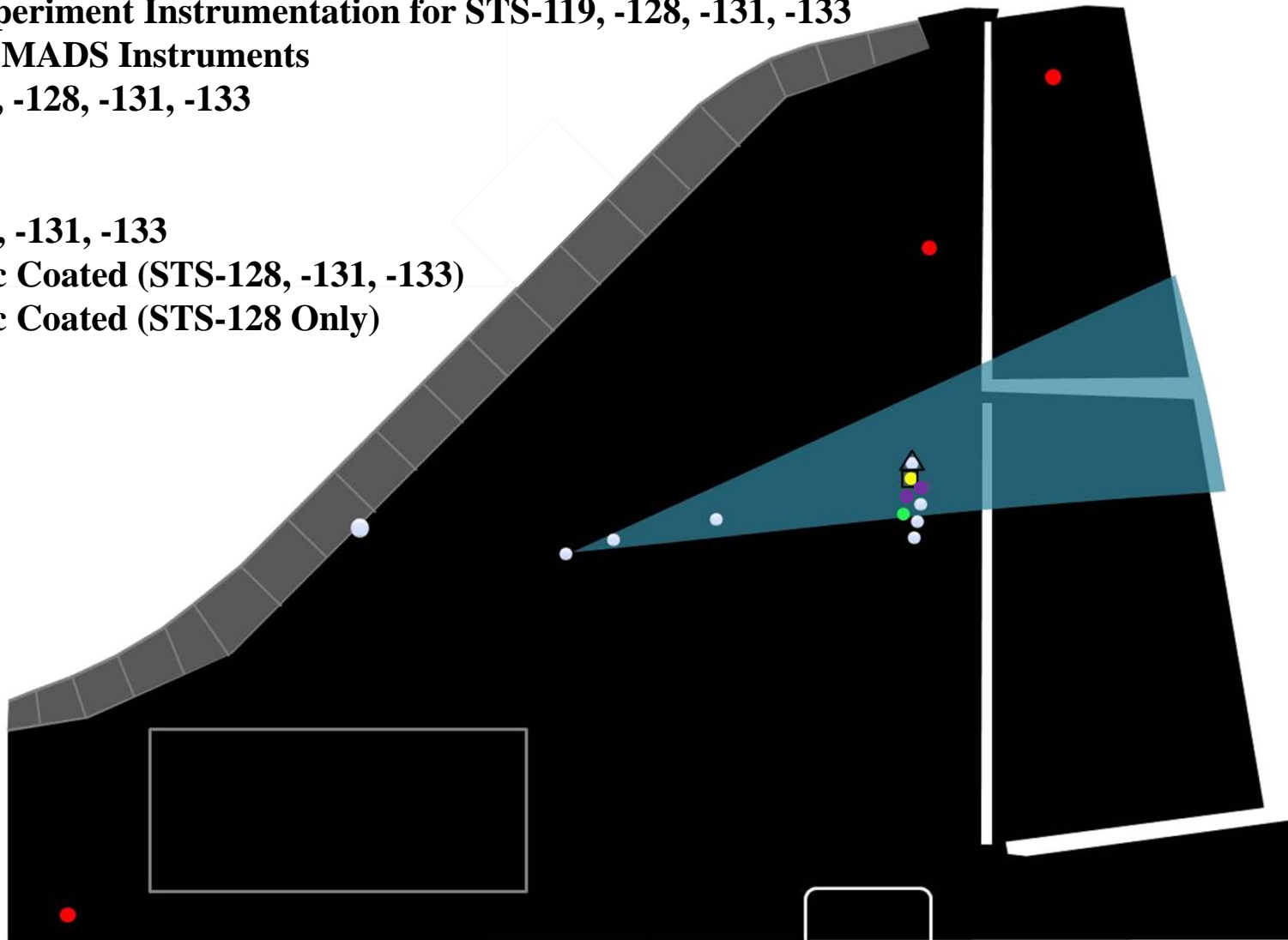


# Design Overview: Instrumentation



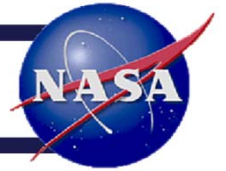
## Flight Experiment Instrumentation for STS-119, -128, -131, -133

- Existing MADS Instruments
- STS-119, -128, -131, -133
- STS-119
- STS-128
- STS-128, -131, -133
- Catalytic Coated (STS-128, -131, -133)
- △ Catalytic Coated (STS-128 Only)

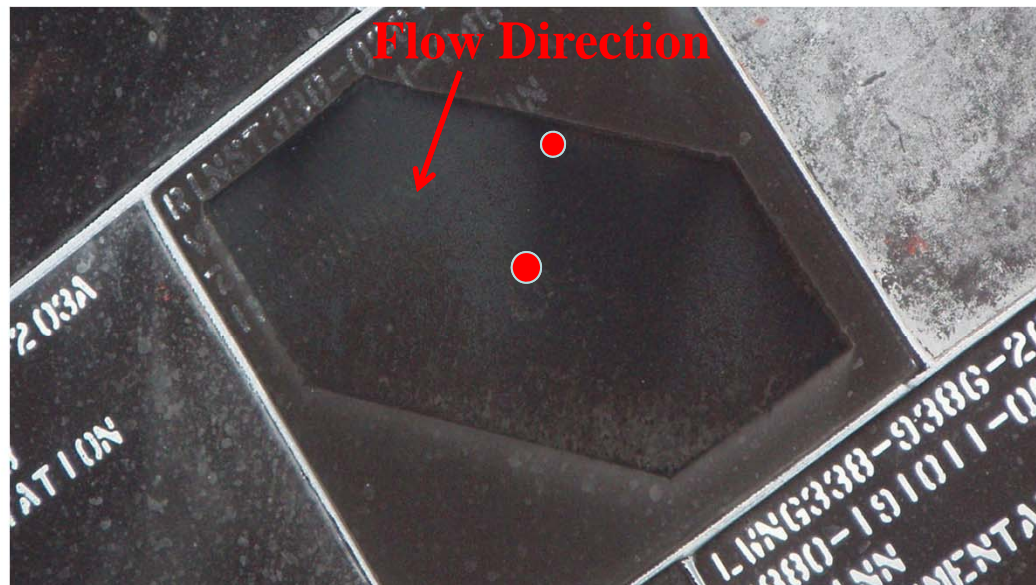




# Design Overview: Catalytic Coating



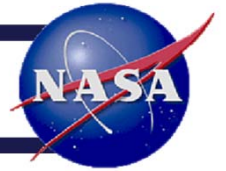
- Complementary test performed to study coupling behavior of catalytic material in fully turbulent flow
  - Results could aid in design of Orion back shell
- Laminar catalytic behavior studied during STS-2, -3, and -5. BLT relatively late in trajectory
- Fully-catalytic coating material applied to tiles downstream of protuberance in predicted turbulent wedge
  - Coating formulation established/tested based on material use on early flight tests
  - Applied on STS-128, 131, 133 and 134



● Approximate thermocouple locations



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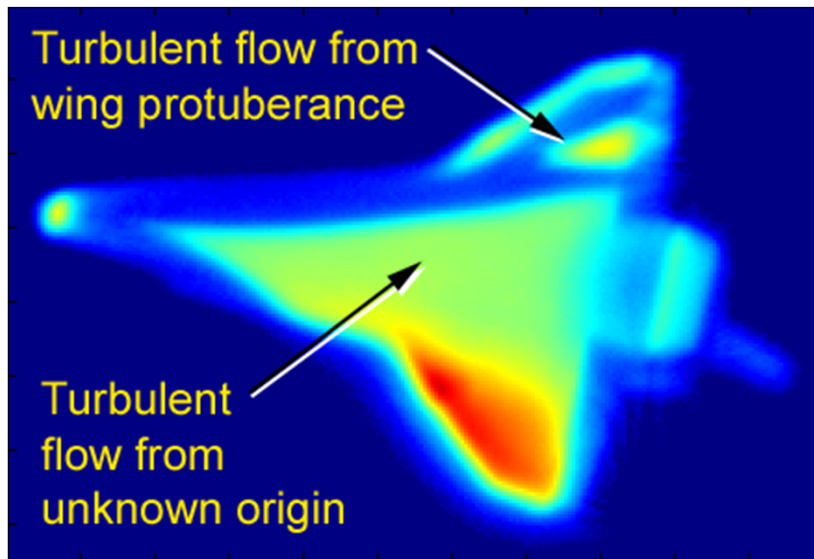
# Review of STS-119



## Protuberance Height: 0.25-inch

### STS-119

- Earliest BLT onset: Mach 15.6
  - Prediction: Mach 15.4
- Maximum measured protuberance temperature: 2012°F
  - Prediction: ~2900°F



- Cause of temperature over-prediction unknown.
- ~1 month to review data, revise models, perform adequately rigorous analysis
- Ad-hoc approach developed to force combination of engineering and CFD analyses to match STS-119 flight data using “knock down” factors

$$\dot{q} = \dot{q}_{XF0002} [(BF_{CFD} - 1)k + 1]$$

- Knock down factors applied to STS-128 analysis using CFD solutions for 0.35” protuberance



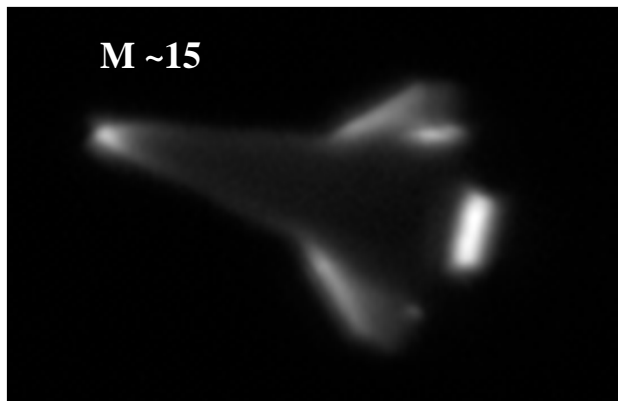
# Review of STS-128 and STS-131



Protuberance Height: 0.35-inch

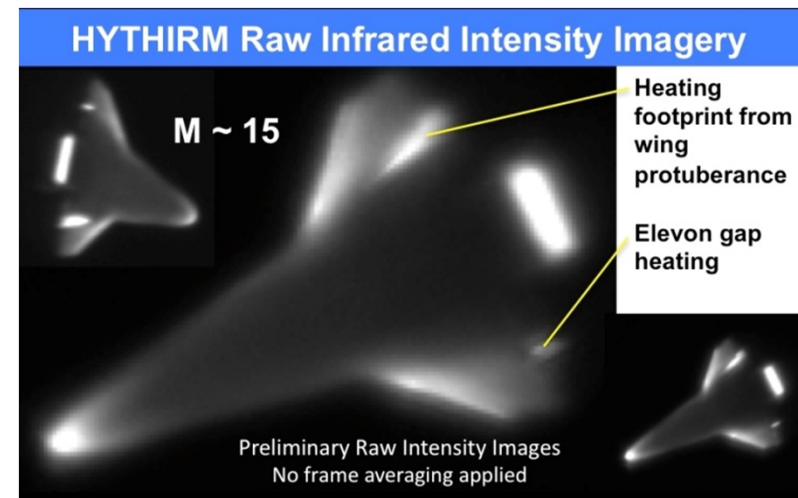
## STS-128

- Earliest BLT onset: Mach 17.5
  - Prediction: Mach 17.4
- Thermocouple anomaly prevented determination of peak laminar temperature
  - Resulted in rapid shift down in data at 350 seconds, same time as roll reversal
  - Seen intermittently on previous shuttle flights, cause unknown



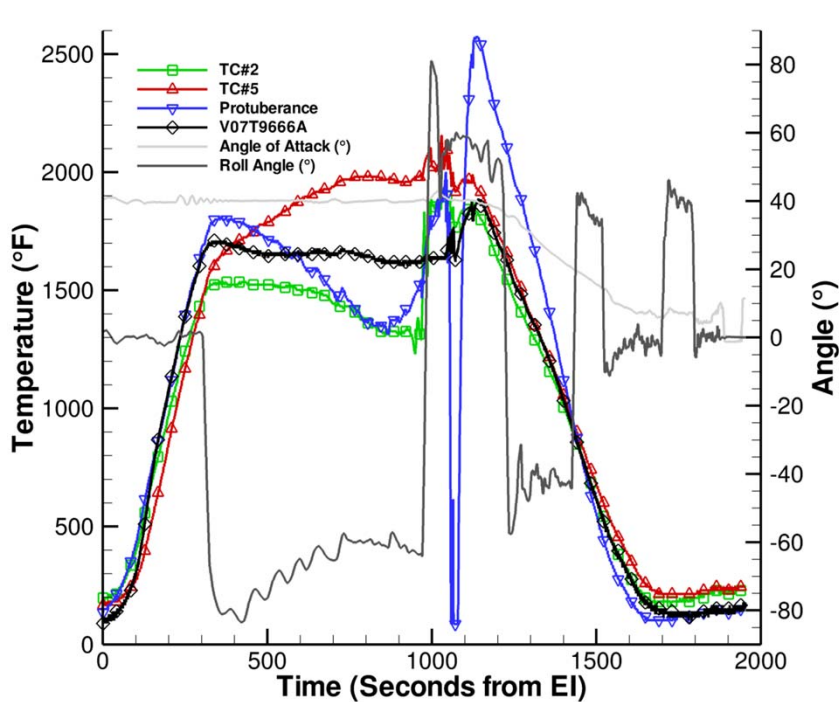
## STS-131

- Earliest BLT onset: Mach 17.4
  - Prediction: Mach 17.2
- Maximum measured protuberance temperature: 2197°F
  - Prediction: ~2650°F

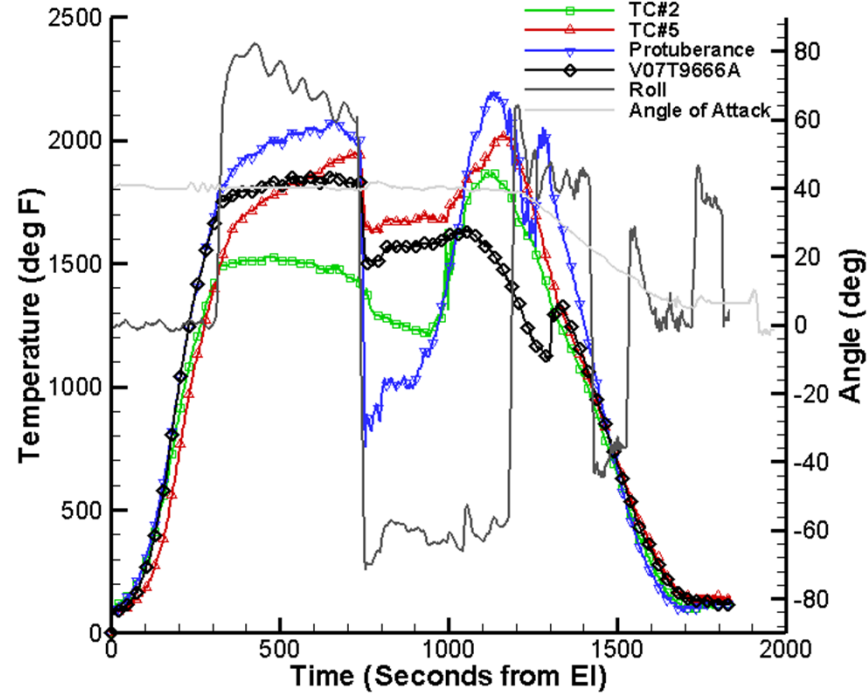




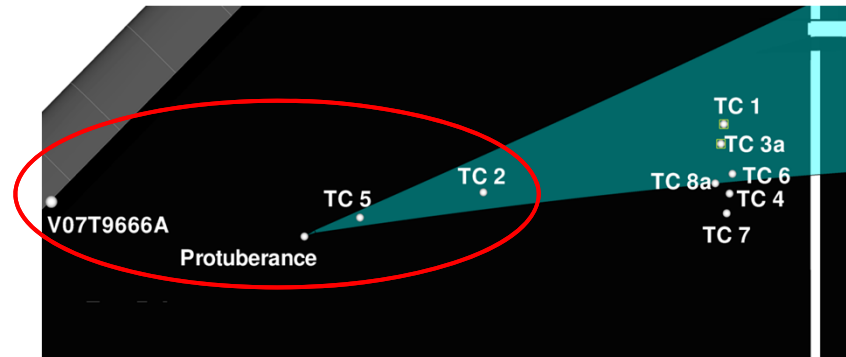
# Thermocouple Anomaly



STS-128 Forward Thermocouples



STS-131 Forward Thermocouples





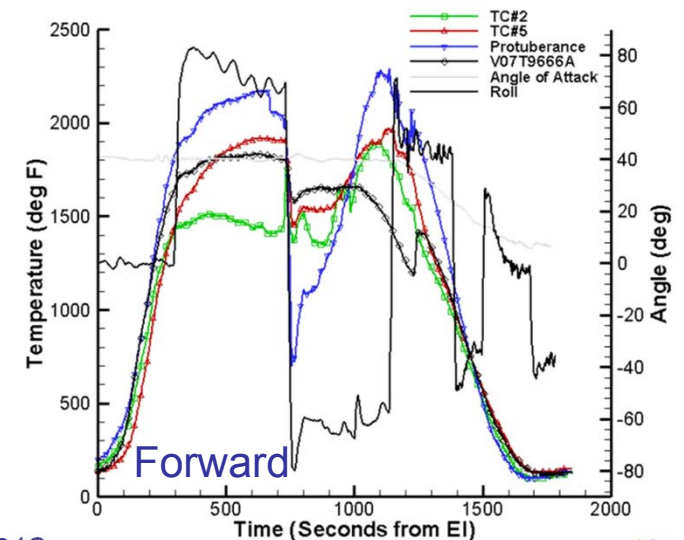
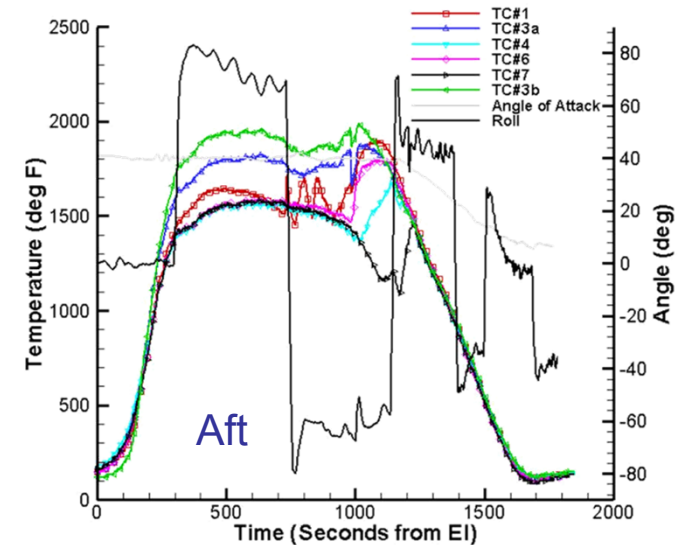
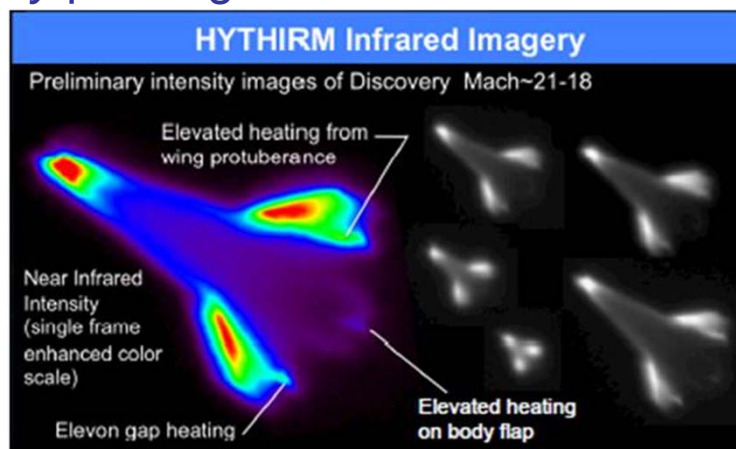
# Review of STS-133



## Protuberance Height: 0.50-inch

### STS-133

- Earliest BLT onset: Mach 19.6
  - Prediction: Mach 19.2
- Maximum measured protuberance temperature: 2288°F (protuberance BLT Mach 8.3)
  - Prediction: ~2870°F (assumes Mach 13.2 protuberance BLT – pre-flight certification)
  - Prediction: ~2310°F (assumes Mach 8.3 protuberance BLT – post-flight analysis)
- Protuberance and catalytic coating tiles left on *Discovery* post-flight





# Outline



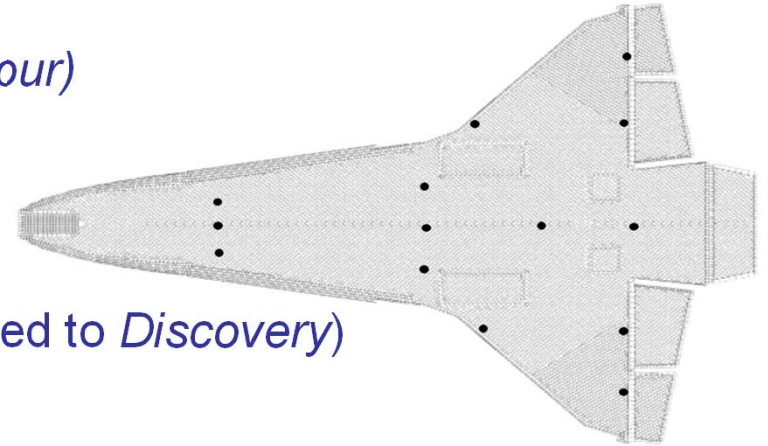
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# Preparations for STS-134

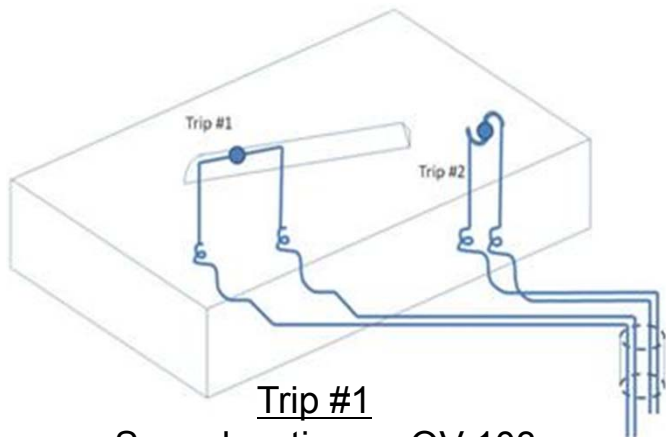


- BLT “lite” approved for flight on STS-134 (*Endeavour*)
- Same protuberance height as STS-133 (0.5-inch)
  - Rapid turn-around time between flights
  - Allow for repeat data set on different Orbiter
- Four thermocouples added to *Endeavour* (ten added to *Discovery*)
- Single catalytic coating tile
- BRI-18 used for protuberance tile, four LI-900 tiles replaced with LI-2200
- Thermocouple anomaly mitigation attempts included instrumentation changes:
  - S-turn (two TCs) to decrease cross-sectional area – may reduce/eliminate anomaly if due to RF interaction
  - New thermocouples routed through strain gage signal conditioner – attempt to reduce external flow field effects causing bias in ground plane voltage





# Instrumentation for STS-134



Trip #1

- Same location as OV-103

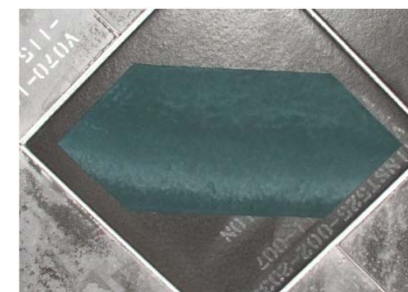
Trip #2:

- New TC location
- On protuberance tile (but not on protuberance or in vortex)
- S-turn



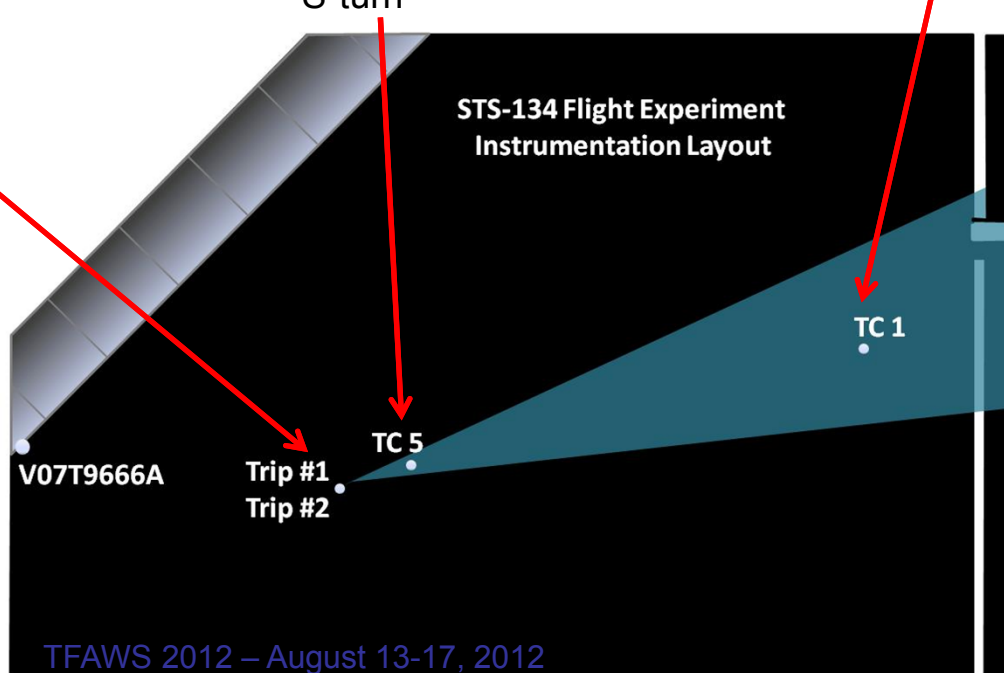
TC #5

- Same location as OV-103
- Exposed TC junction
- S-turn



TC #1

- Same location as OV-103
- Catalytic coating

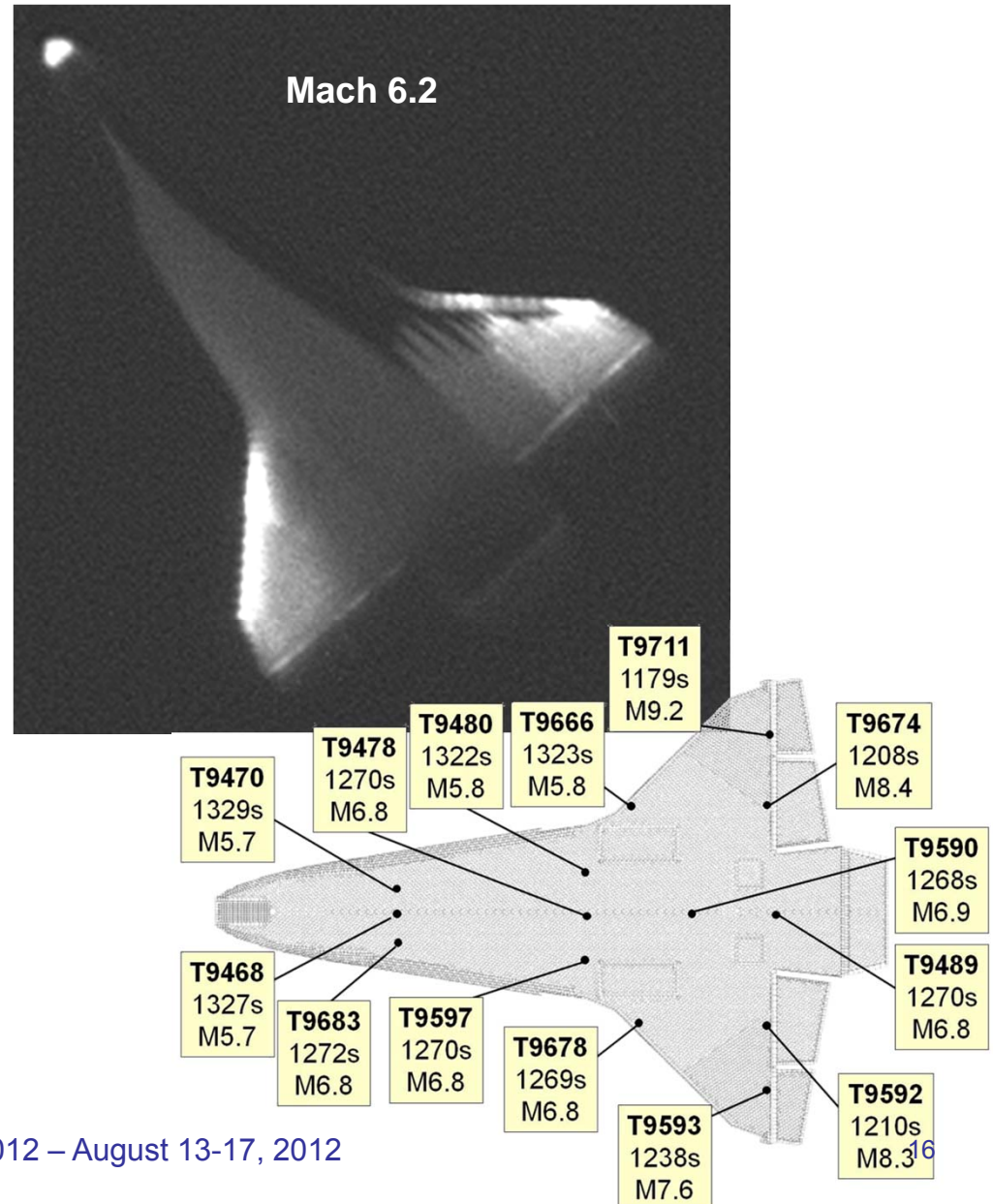




# STS-134 BLT FE Data

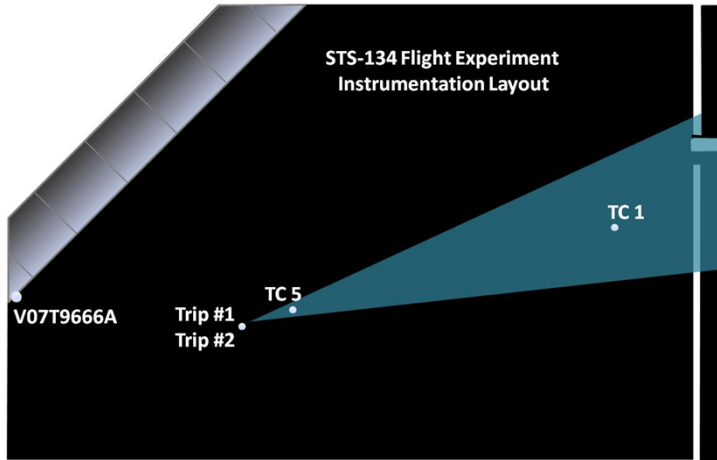


- Launched May 16, 2011
- Landed June 1, 2011 at KSC
- Thermocouple data showed asymmetric BLT over vehicle windward surface
- BLT relatively late over windward surface (~Mach 6-7), indicative of vehicle clean of protruding gap fillers, cavities and/or tile-to-tile steps and gaps
- Reflects significant effort of ground crews to prepare vehicle before flight

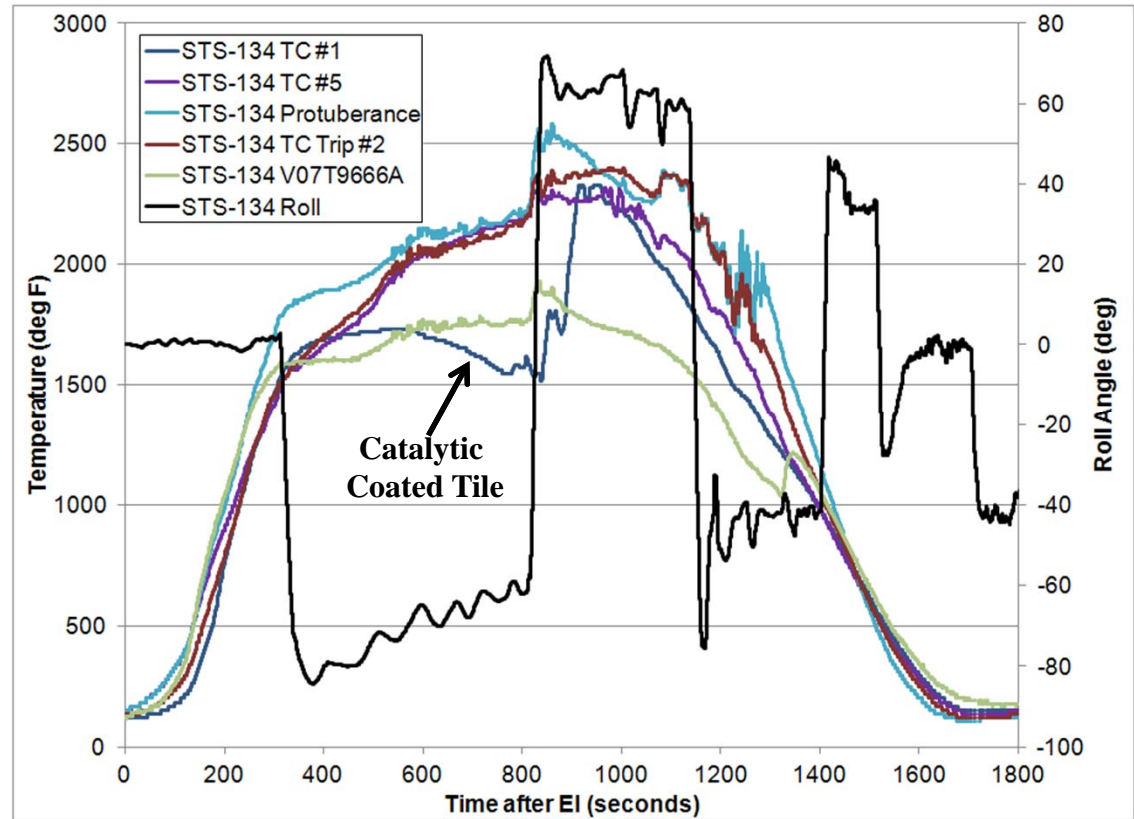




# STS-134 BLT FE Data



TC	Mach	Time (s)
1	19.6 or 18.6	837 or 879
5	15.4	985
Trip 1	8.0	1227
Trip 2	8.0	1227
V0T9666A	5.9	1323

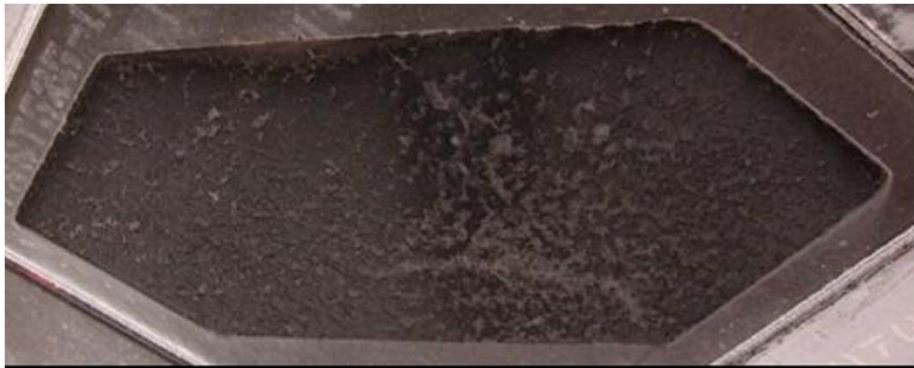




# STS-134 Post Flight Observations

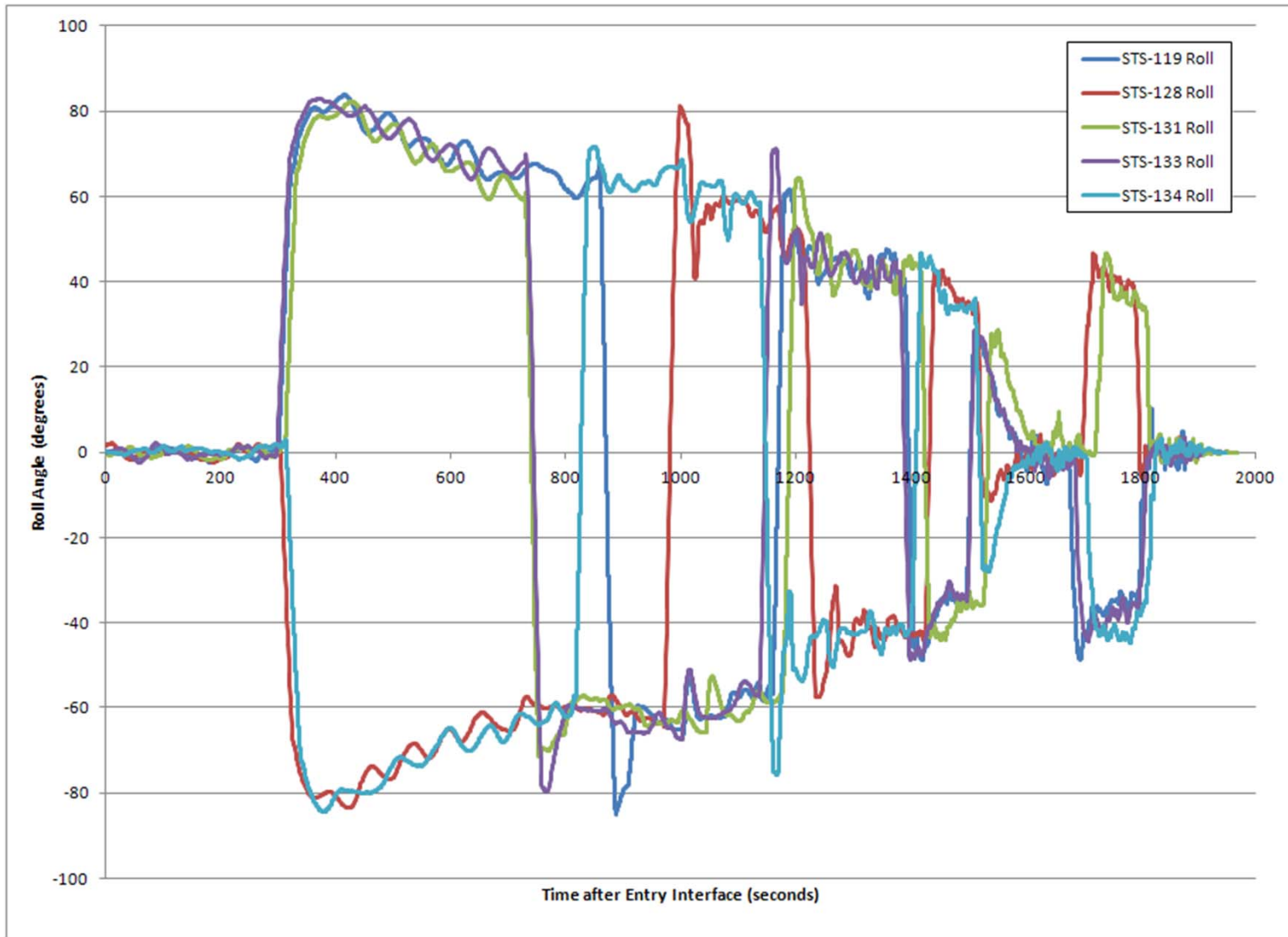


- Earliest BLT onset: Mach 19.6 or 18.6
  - Prediction: Mach 19.2
- Maximum measured protuberance temperature: 2583°F
  - Prediction: ~2800°F
- Temperatures on tile surrounding protuberance did not exceed 2500°F\*
  - Prediction: 2400°F
  - Measured Maximum was 2397°F
- Protuberance and catalytic tiles left on *Endeavour* after the flight





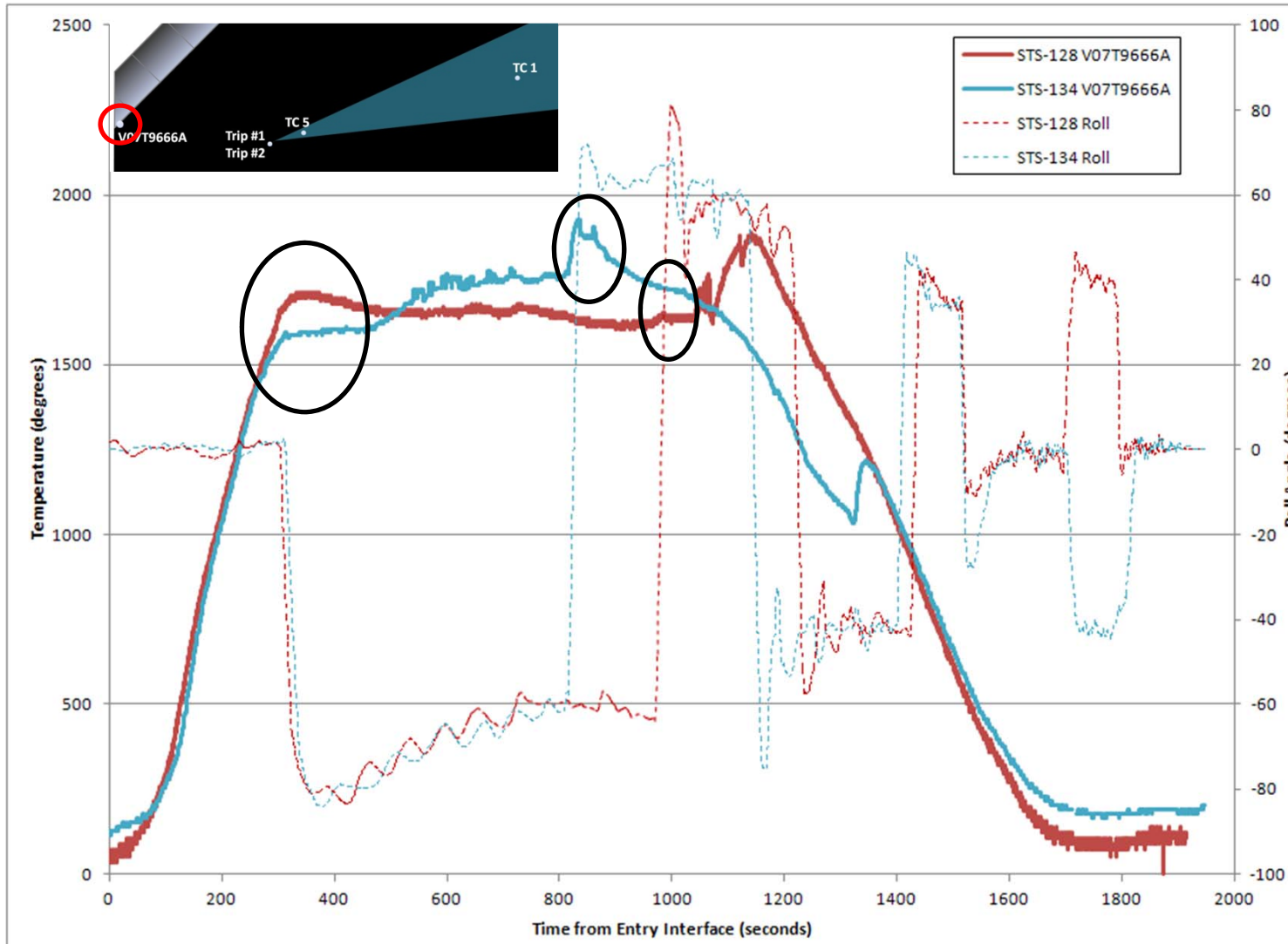
# Comparison of Vehicle Roll Angles



STS-119, STS-131 and STS-133 initially roll positive  
STS-128 and STS-134 initially roll negative



# STS-128 vs. STS-134 (TC9666)



## Instrumentation Differences

none

## Roll Onset (350 sec)

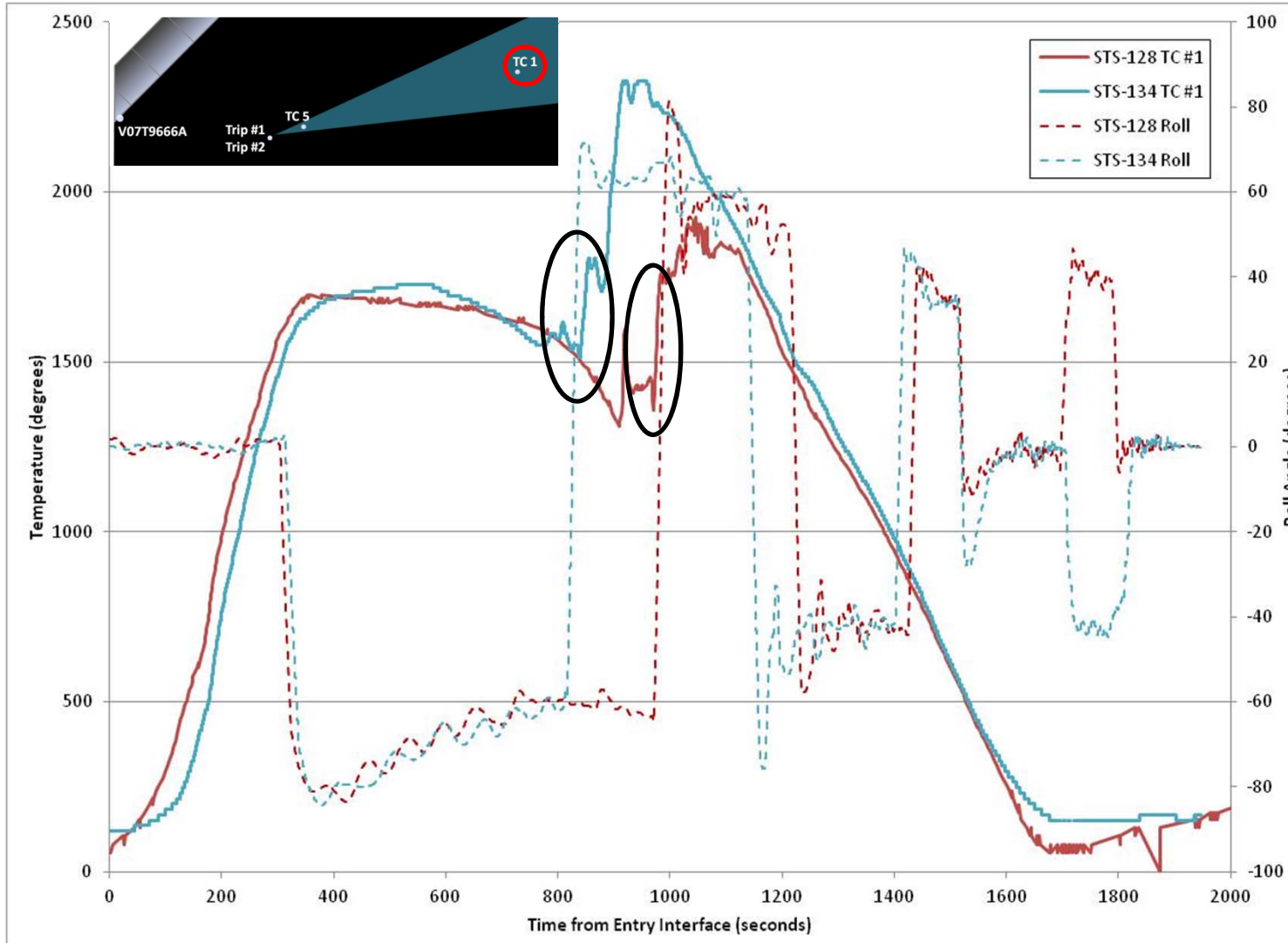
Both flights level out at roll onset

## 1<sup>st</sup> Roll Reversal

Rapid increase for STS-134  
Small increase on STS-128



# STS-128 vs. STS-134 (TC1)

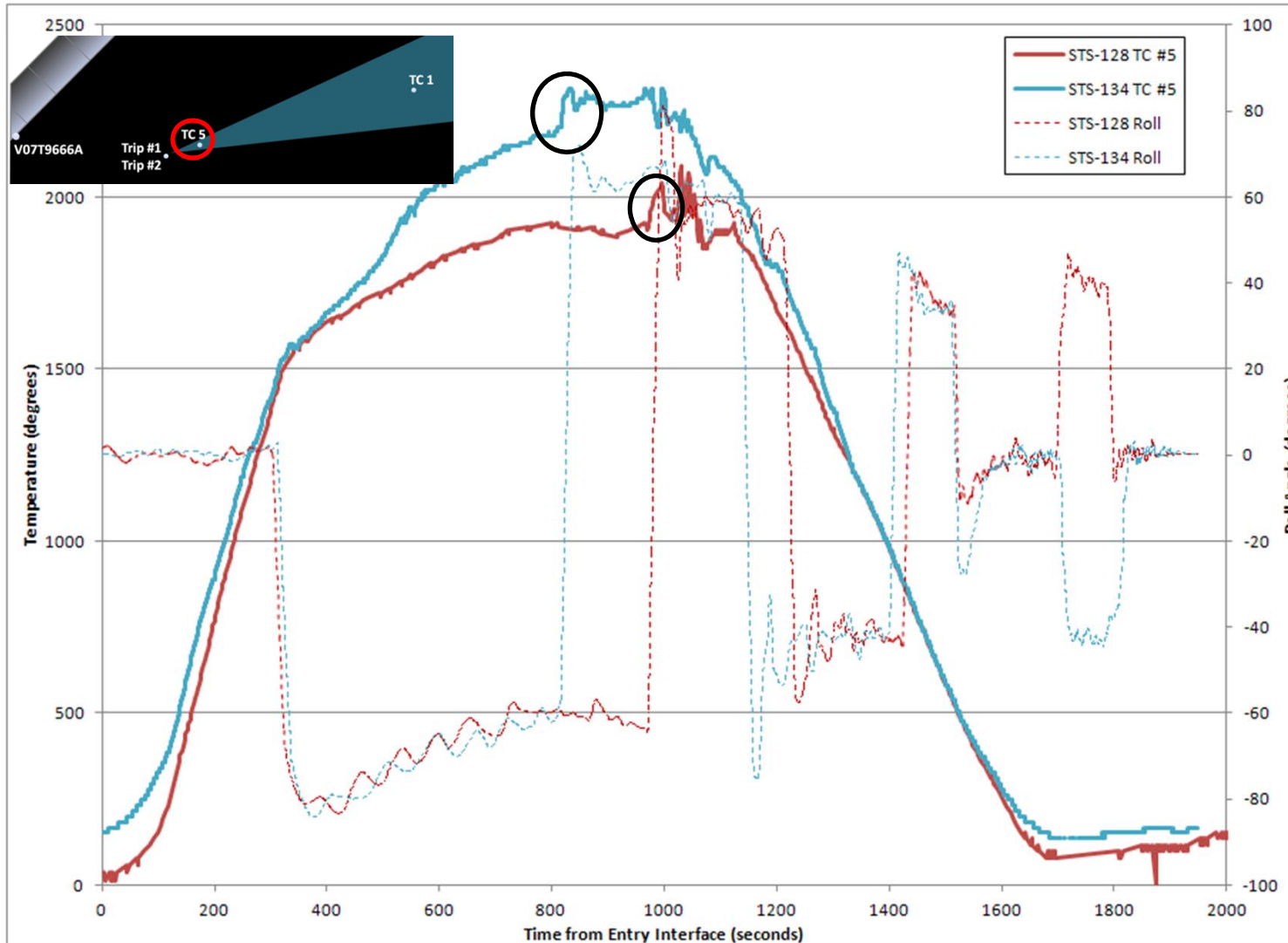


**Instrumentation Differences**  
STS-134 has Strain Gage Signal Conditioner

**1st Roll Reversal**  
Rapid increase for both flights



# STS-128 vs. STS-134 (TC5)



## Instrumentation Differences

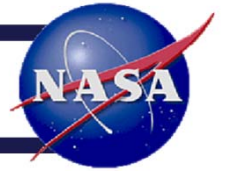
- STS-134 has
- Strain Gage Signal Conditioner
  - S-Turn
  - Exposed TC Junction

## 1<sup>st</sup> Roll Reversal

Rapid increase  
(~100 deg)



# Summary



- Protuberance tile flown on port wing of Orbiter *Discovery* and *Endeavour*
  - 0.25” Protuberance – Mach 15.6 (STS-119)
  - 0.35” Protuberance – Mach 17.5 (STS-128), Mach 17.4 (STS-131)
  - 0.50” Protuberance – Mach 19.6 (STS-133), Mach 19.6 or 18.6 (STS-134)
- Catalytic coating material flown on STS-128, STS-131, STS-133 and STS-134
- BLT onset time predictions match favorably with flight data
- Temperature predictions significantly higher than measured data except for -134
- Thermocouple anomaly resulting in rapid or gradual temperature shifts observed on all BLT flights – makes interpretation of flight data difficult
  - Seems to correlate with vehicle roll reversal maneuvers
  - May be roll direction dependent
- Changes to instrumentation, including S-turn layout and use of strain gage signal conditioner did not seem to have a significant mitigation effect on the anomaly
- Protuberance, Catalytic Coating tiles left on *Discovery* and *Endeavour*