



Space Shuttle Boundary Layer Transition Flight Experiment Overview

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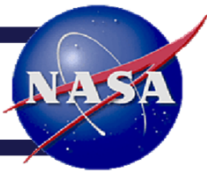
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Jet Propulsion Laboratory
Pasadena, CA





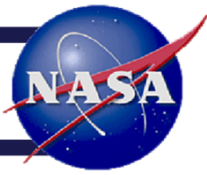
Outline



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



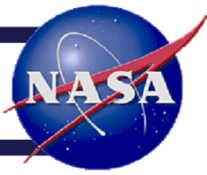
Introduction and Motivation



- 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 approved for *Discovery* only and *Endeavour* added later



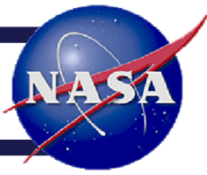
Design Overview: Protuberance



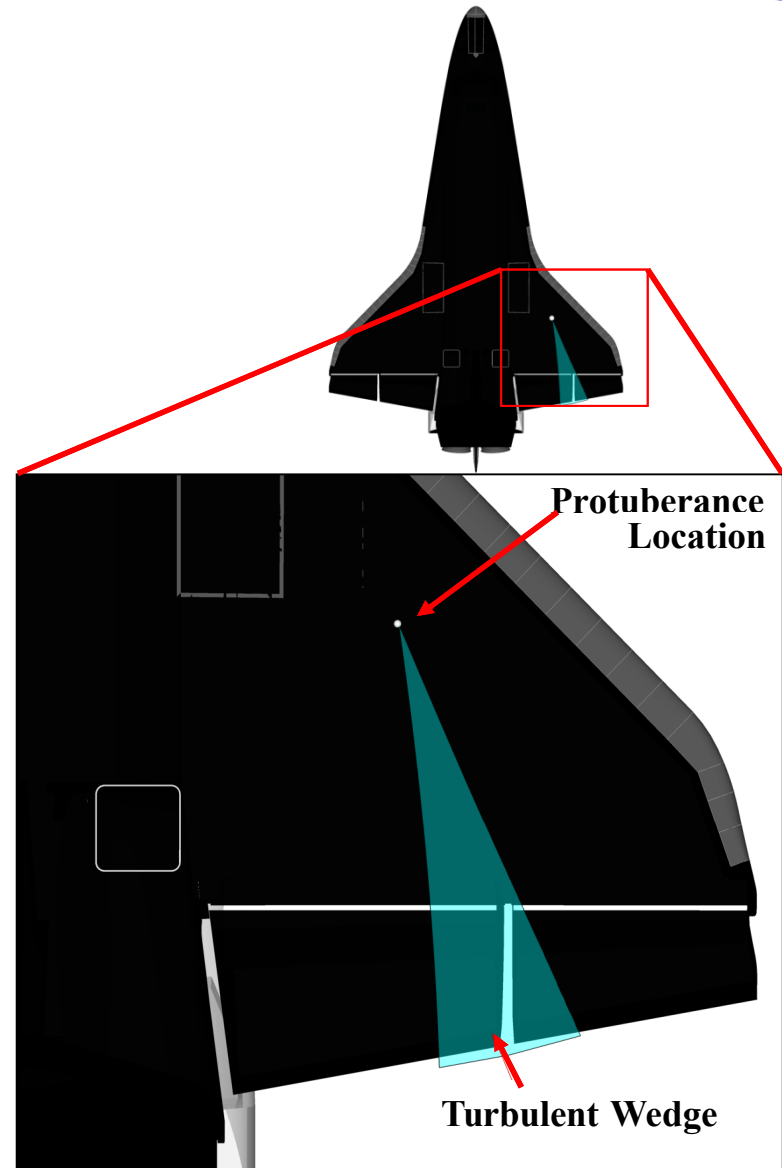
- Incremental approach to flight test for safety
- Protuberance height derived with RTF BLT tool
 - Re_θ/M_e correlation using best estimate coefficient
 - First flight: 0.25 inches (~Mach 15)
 - Second/Third flights: 0.35 inches (~Mach 18)
 - Fourth/Fifth flights: 0.50 inches (~Mach 19.2)



Design Overview: Placement



- Top design priority 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 $< 1:10,000$



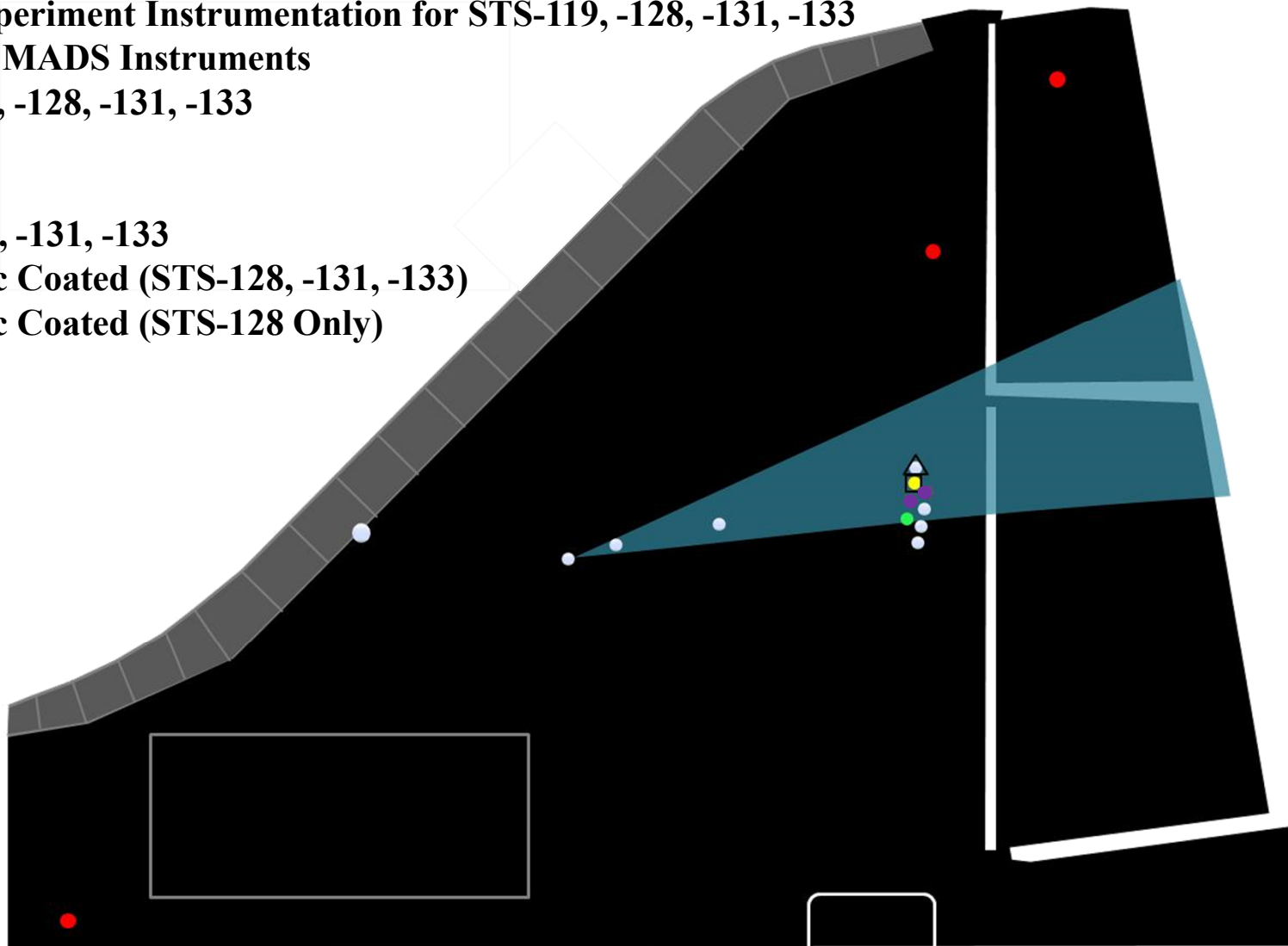


Design Overview: Instrumentation



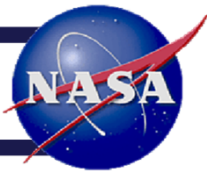
Flight Experiment Instrumentation for STS-119, -128, -131, -133

- 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)

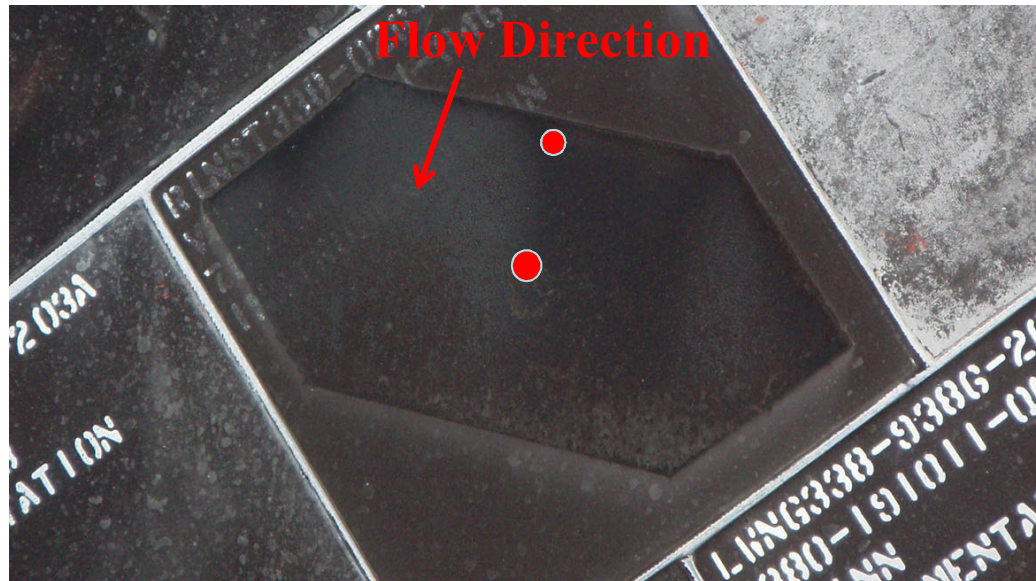




Design Overview: Catalytic Coating



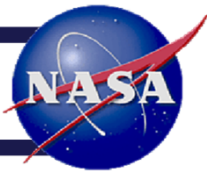
- Complementary test performed to study coupling behavior of catalytic material in fully turbulent flow
 - Results could aid in design of Orion back shell
- Laminar catalytic behavior studied during STS-2, -3, and -5. BLT relatively late in trajectory
- Fully-catalytic coating material applied to tiles 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



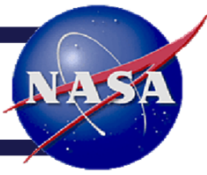
● Approximate thermocouple locations



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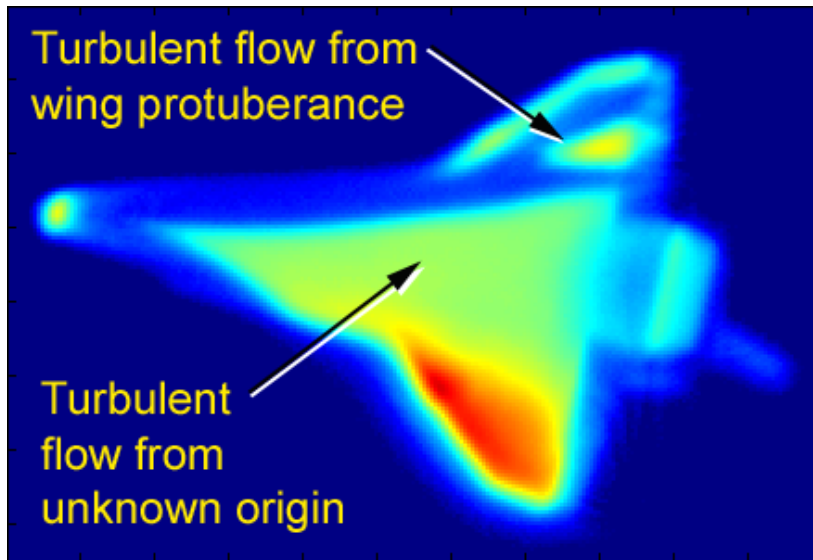


Review of STS-119

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



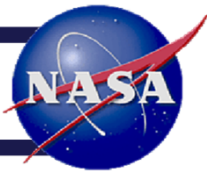
- Unknown cause of temperature over-prediction unknown.
- ~1 month to review data, revise models, perform adequately rigorous analysis
- Ad-hoc approach developed to force combination of engineering and CFD analyses to match STS-119 flight data using “knock down” factors

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

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



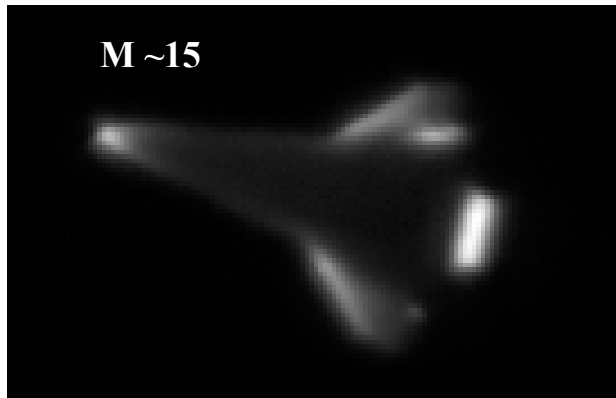
Review of STS-128 and STS-131



Protuberance Height: 0.35-inch

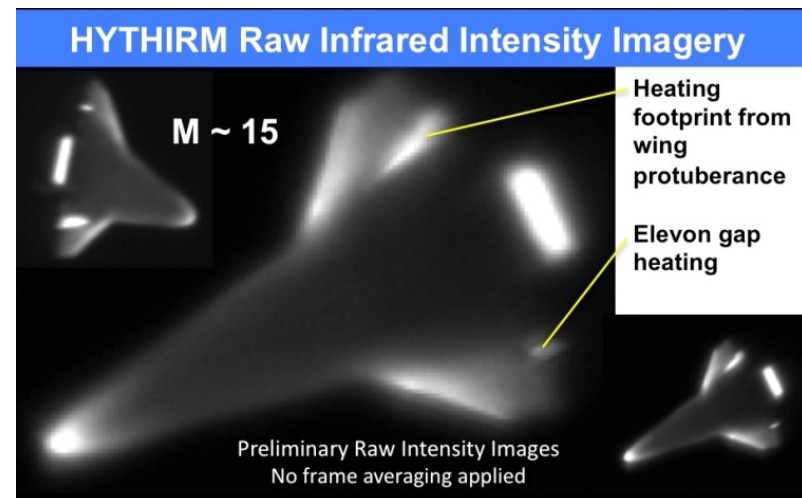
STS-128

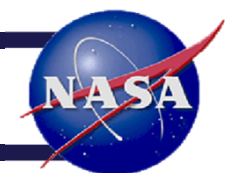
- Earliest BLT onset: Mach 17.5
 - Prediction: Mach 17.4
- Thermocouple anomaly prevented determination of peak laminar temperature
 - Resulted in rapid shift down in data at 350 seconds, same time as roll reversal
 - Seen intermittently on previous shuttle flights, cause unknown



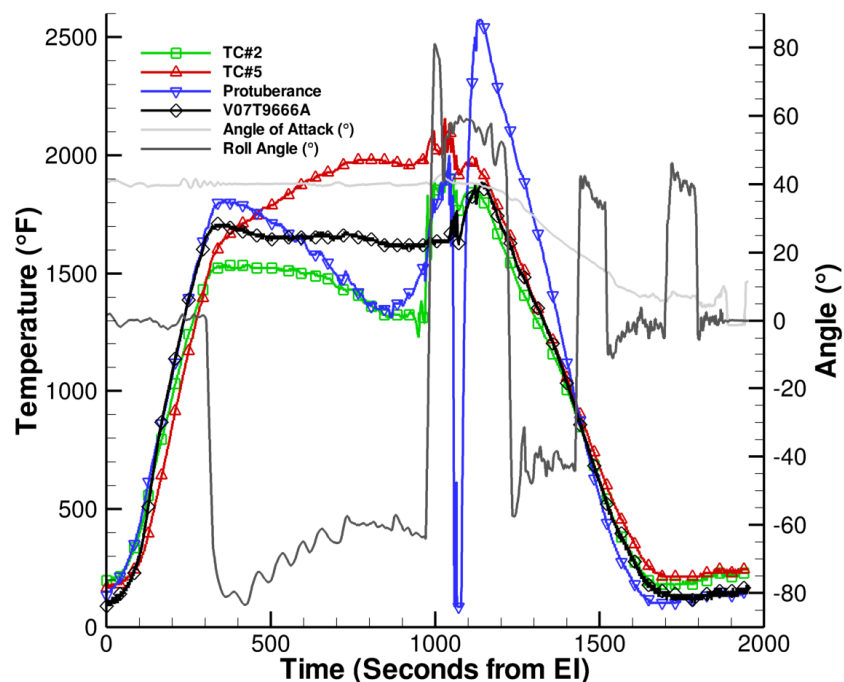
STS-131

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

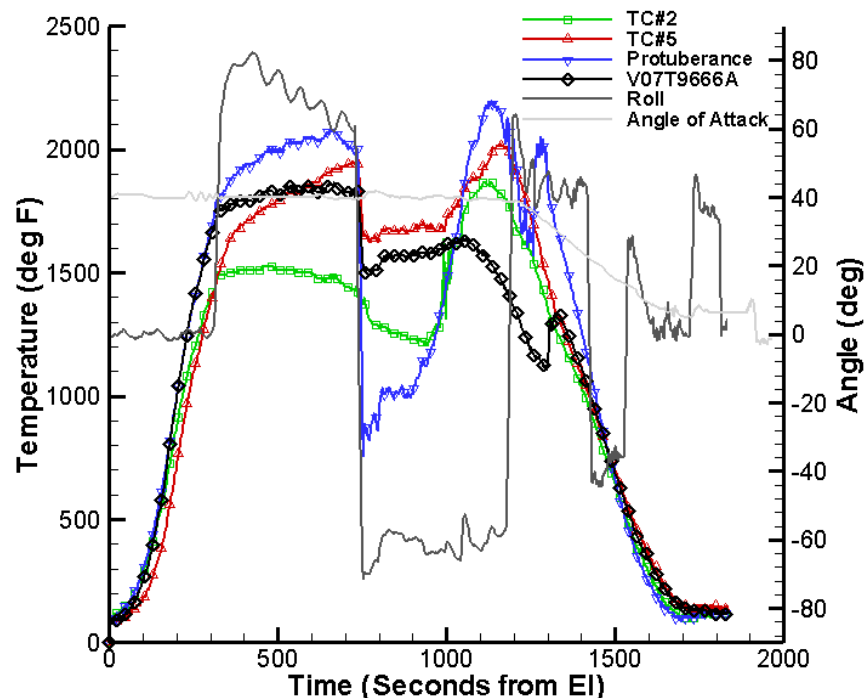




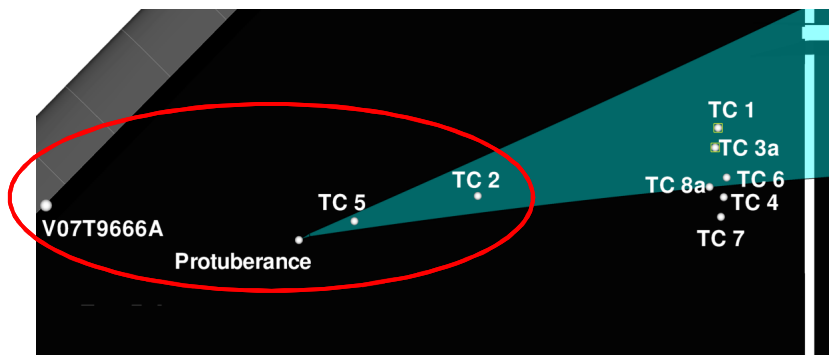
Thermocouple Anomaly



STS-128 Forward Thermocouples



STS-131 Forward Thermocouples





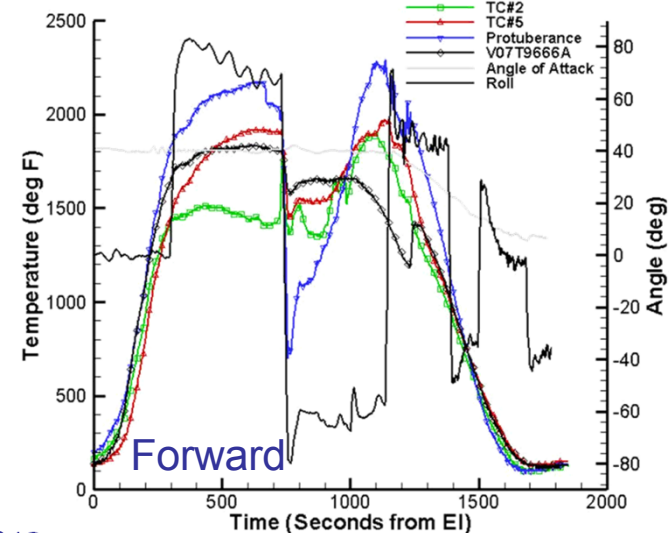
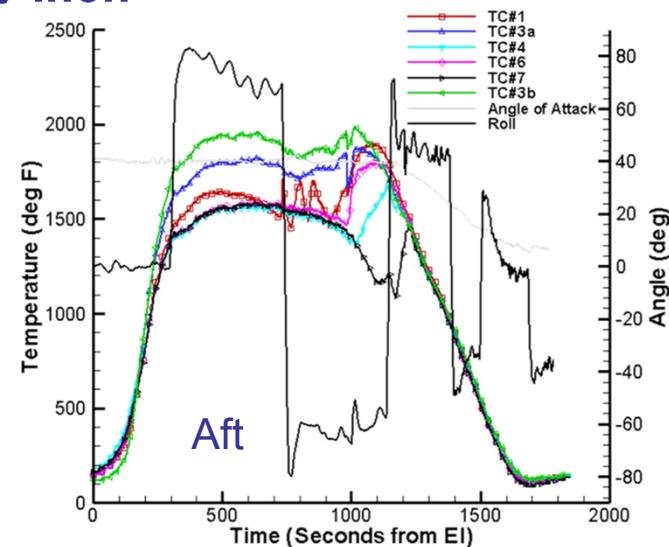
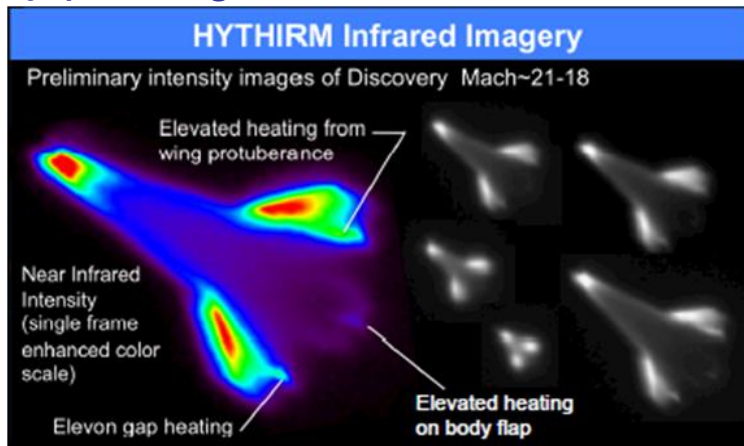
Review of STS-133



Protuberance Height: 0.50-inch

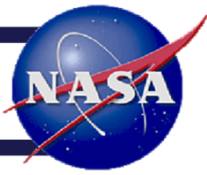
STS-133

- 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





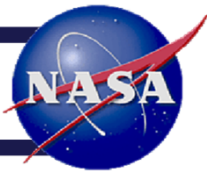
Outline



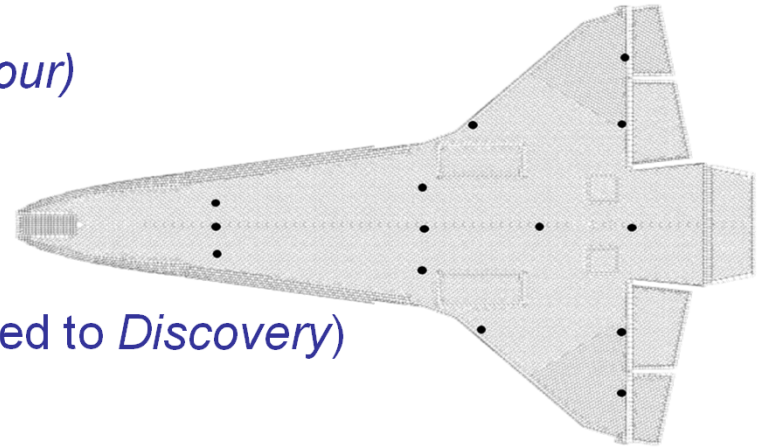
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Preparations for STS-134

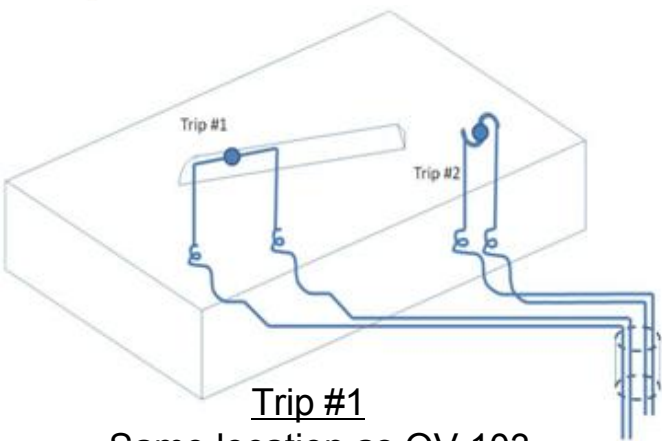
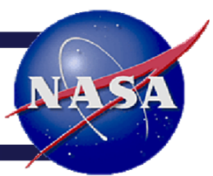


- BLT “lite” approved for flight on STS-134 (*Endeavour*)
- Same protuberance height as STS-133 (0.5-inch)
 - Rapid turn-around time between flights
 - Allow for repeat data set on different Orbiter
- Four thermocouples added to *Endeavour* (ten added to *Discovery*)
- Single catalytic coating tile
- 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

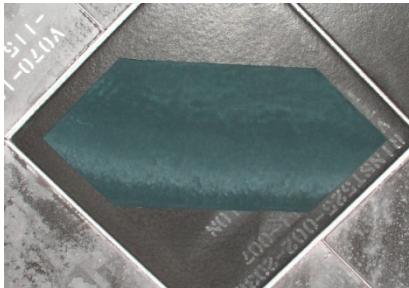
Trip #2:

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



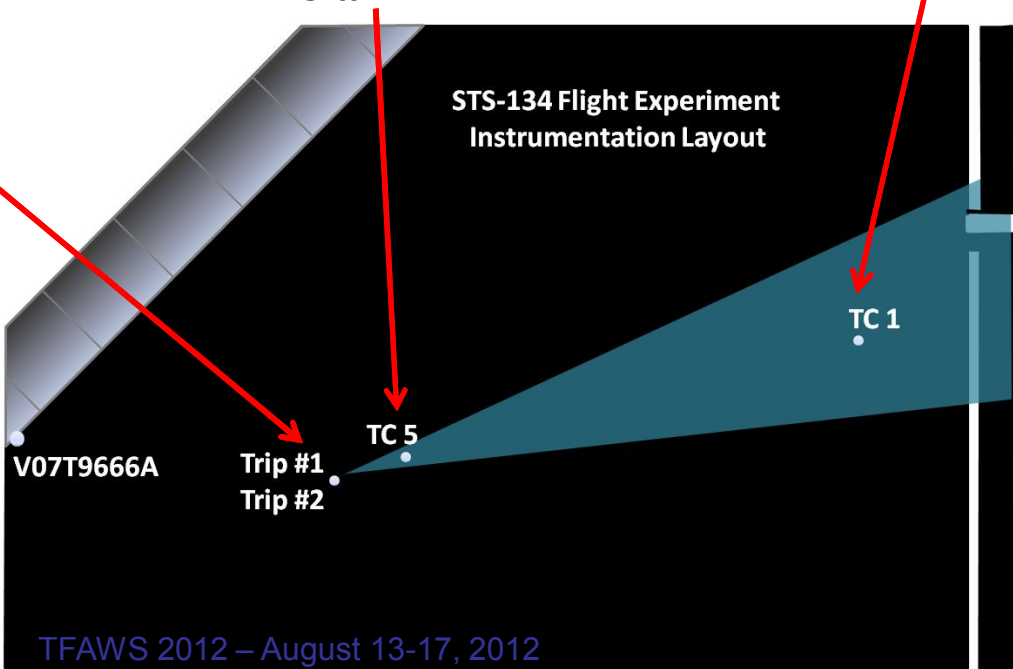
TC #5

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



TC #1

- Same location as OV-103
- Catalytic coating



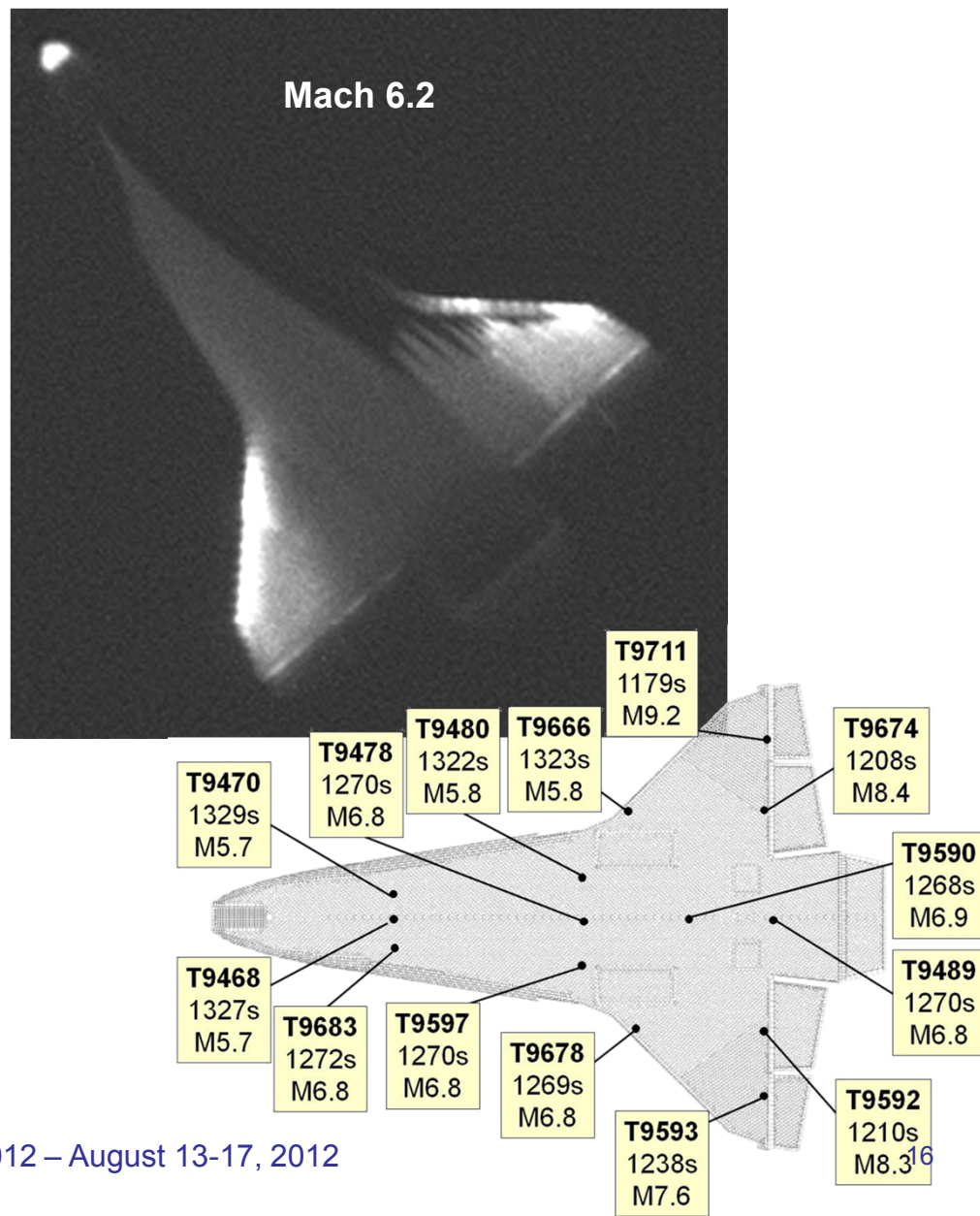
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STS-134 BLT FE Data



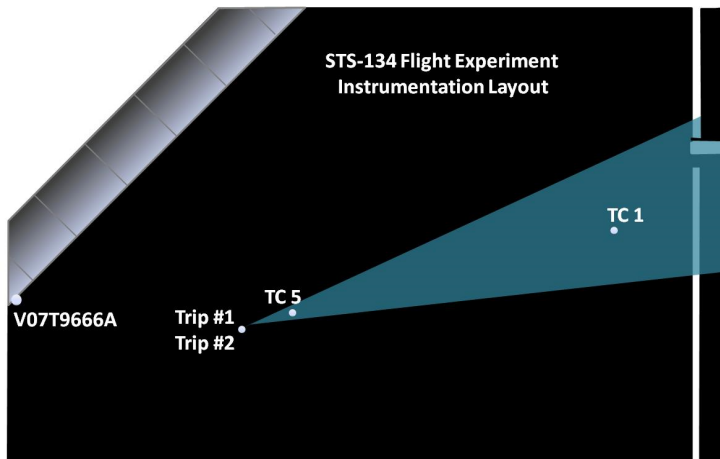
- Launched May 16, 2011
- Landed June 1, 2011 at KSC
- Thermocouple data showed asymmetric BLT over vehicle windward surface
- BLT relatively late over windward surface (~Mach 6-7), indicative of vehicle clean of protruding gap fillers, cavities and/or tile-to-tile steps and gaps
- Reflects significant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



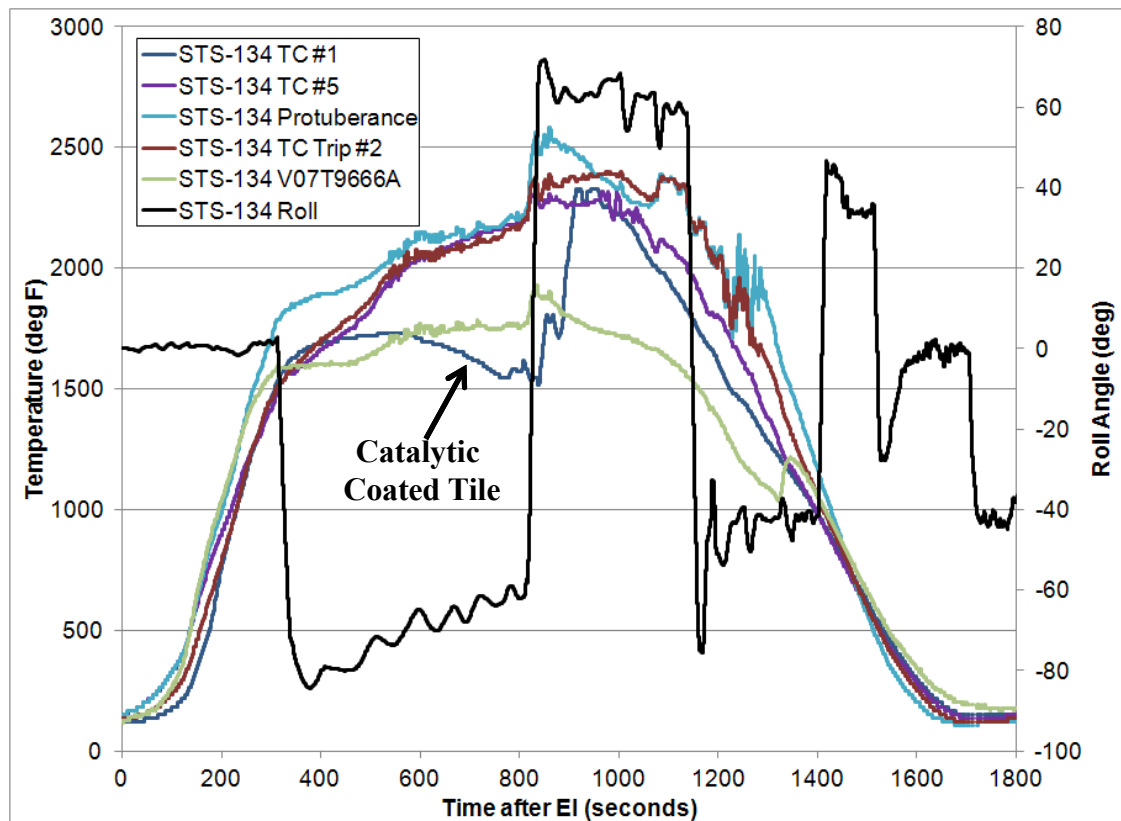
TFAWS 2012 – August 13-17, 2012



STS-134 BLT FE Data

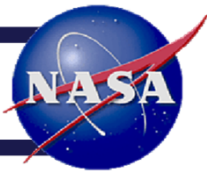


TC	Mach	Time (s)
1	19.6 or 18.6	837 or 879
5	15.4	985
Trip 1	8.0	1227
Trip 2	8.0	1227
V07T9666A	5.9	1323





STS-134 Post Flight Observations

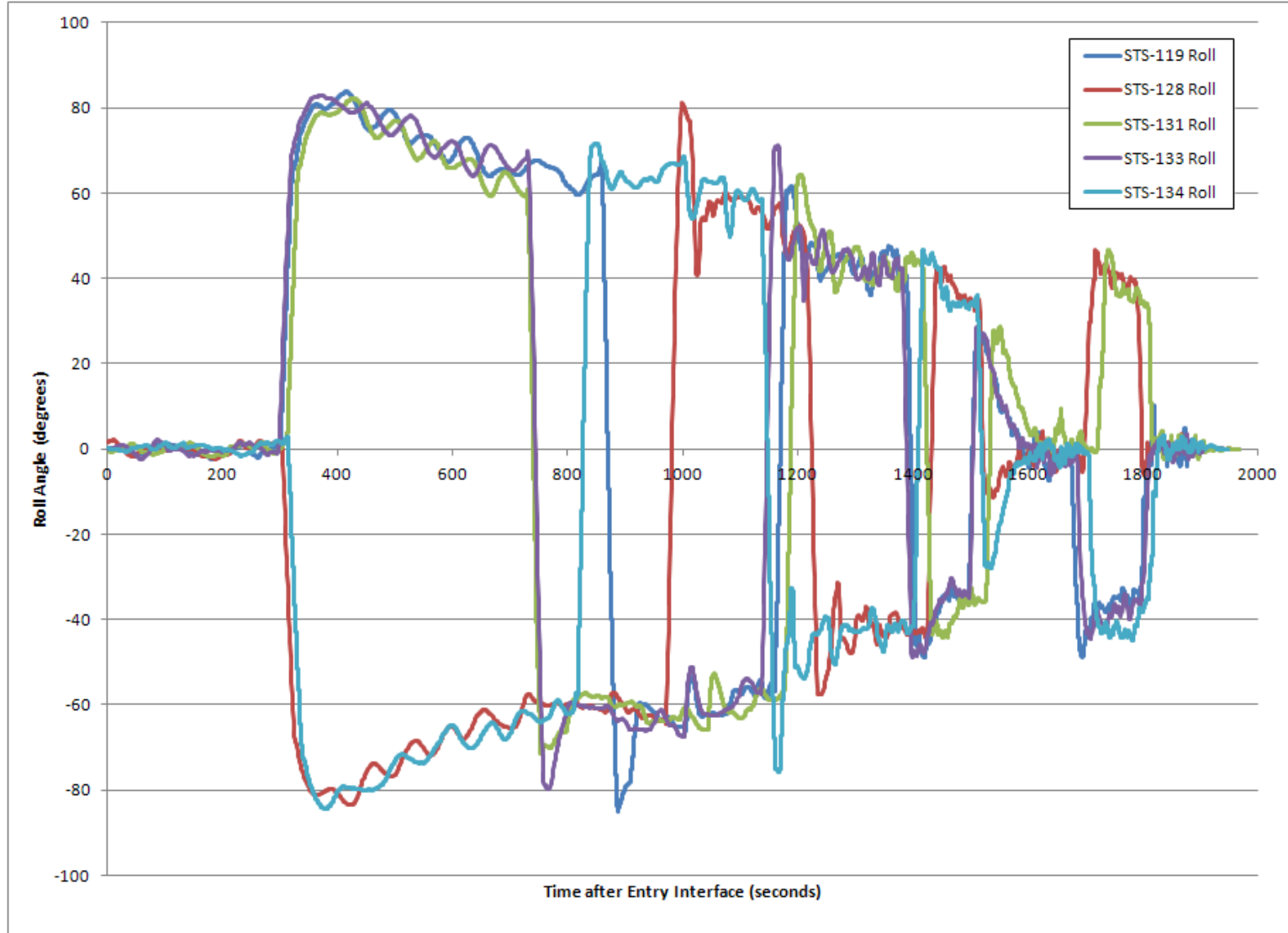
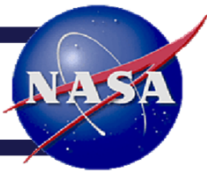


- Earliest BLT onset: Mach 19.6 or 18.6
 - Prediction: Mach 19.2
- Maximum measured protuberance temperature: 2583°F
 - Prediction: ~2800°F
- Temperatures on tile surrounding protuberance did not exceed 2500°F*
 - Prediction: 2400°F
 - Measured Maximum was 2397°F
- Protuberance and catalytic tiles left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





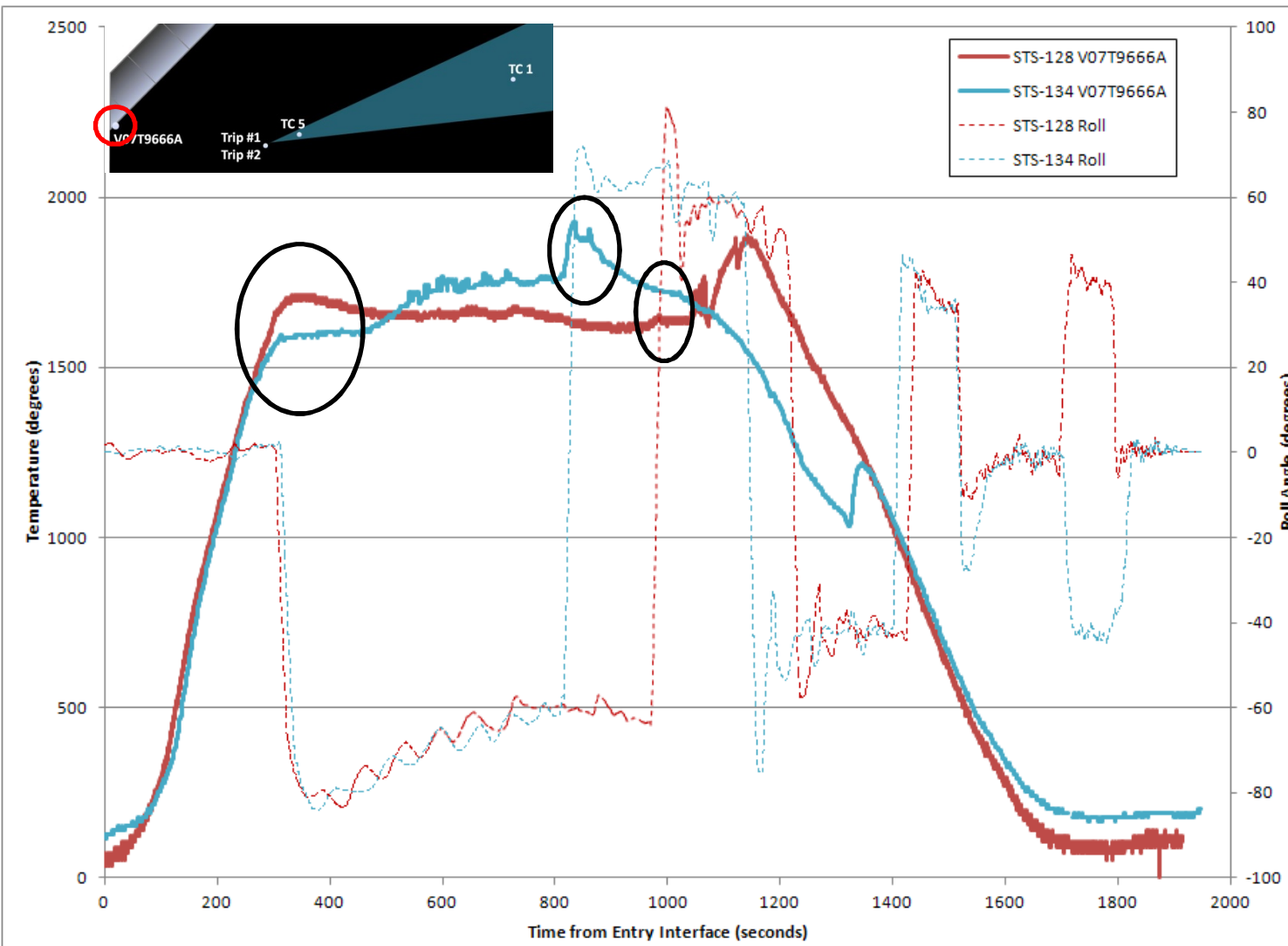
STS-128 and STS-134 (Roll Angle)



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



STS-128 vs. STS-134 (TC9666)



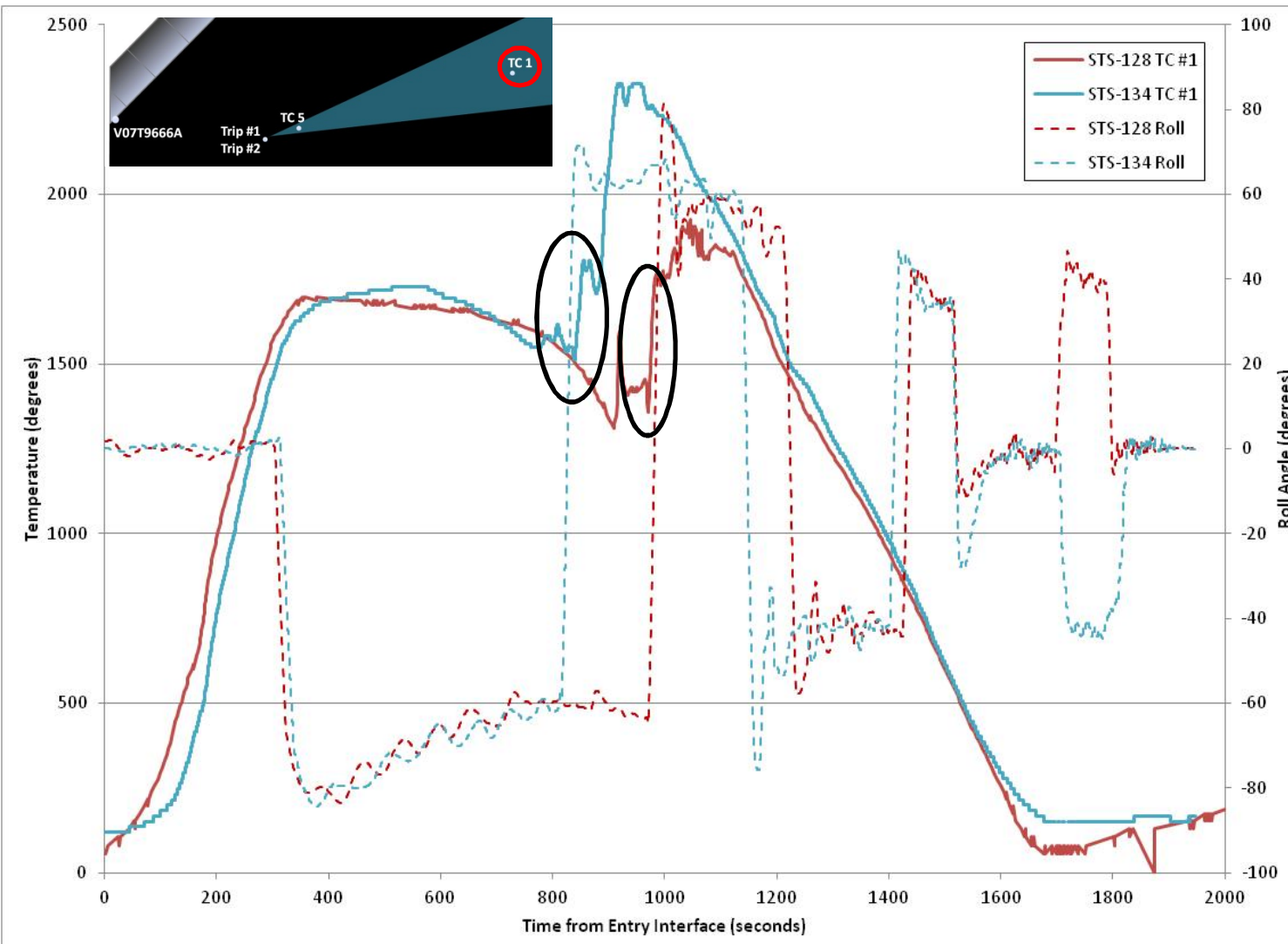
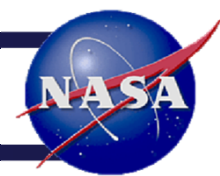
Instrumentation Differences
none

Roll Onset (350 sec)
Both flights level out at roll onset

1st Roll Reversal
Rapid increase for STS-134
Small increase on STS-128



STS-128 vs. STS-134 (TC1)



Instrumentation Differences

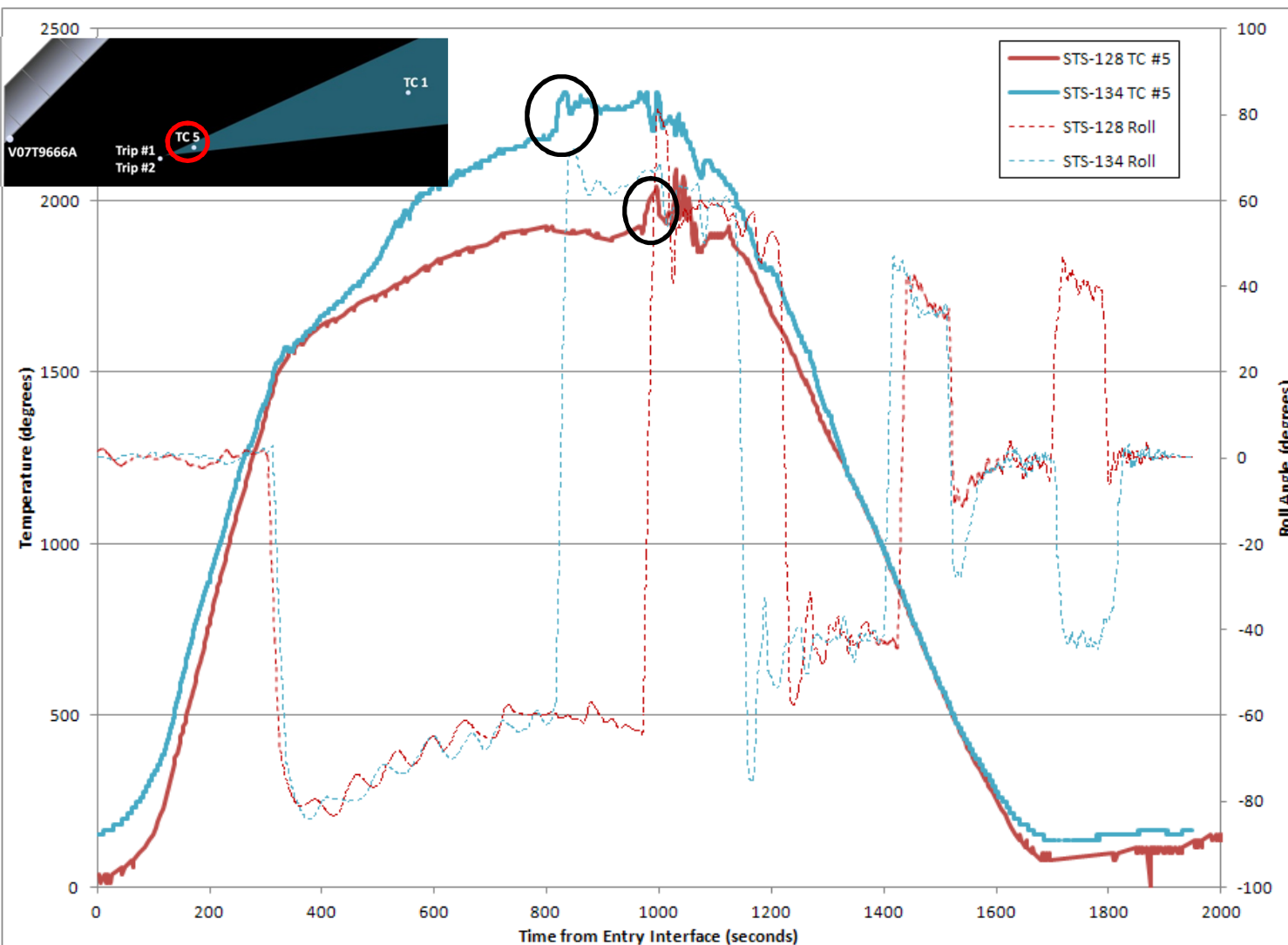
STS-134 has Strain Gage Signal Conditioner

1st Roll Reversal

Rapid increase for both flights



STS-128 vs. STS-134 (TC5)



Instrumentation Differences

STS-134 has

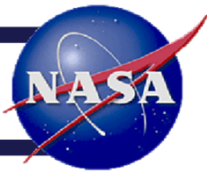
- Strain Gage Signal Conditioner
- S-Turn
- Exposed TC Junction

1st Roll Reversal

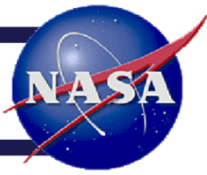
Rapid increase
(~100 deg)



Summary



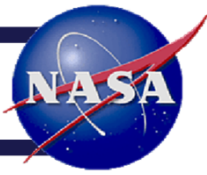
- Protuberance tile flown on port wing of Orbiter *Discovery* and *Endeavour*
 - 0.25" Protuberance – Mach 15.6 (STS-119)
 - 0.35" Protuberance – Mach 17.5 (STS-128), Mach 17.4 (STS-131)
 - 0.50" Protuberance – Mach 19.6 (STS-133), Mach 19.6 or 18.6 (STS-134)
- Catalytic coating material flown on STS-128, 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*



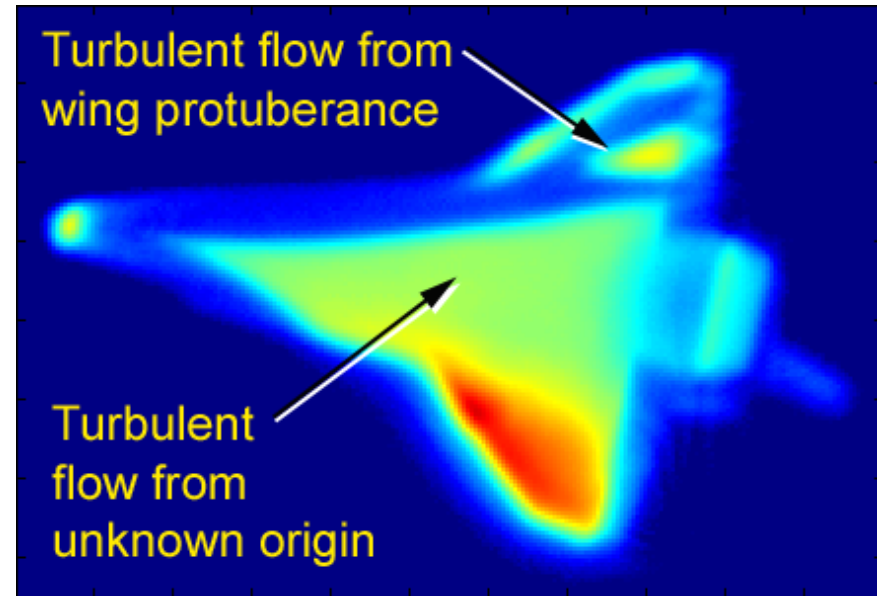
Back Up Slides



STS-119 BLT FE Data

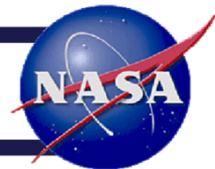


- Launched March 14, 2009
- Landed March 28, 2009 at KSC
- Post-flight review of thermocouple data showed asymmetric BLT on starboard side at Mach 11.5
- Cause of event unknown
- Did not affect flight experiment data

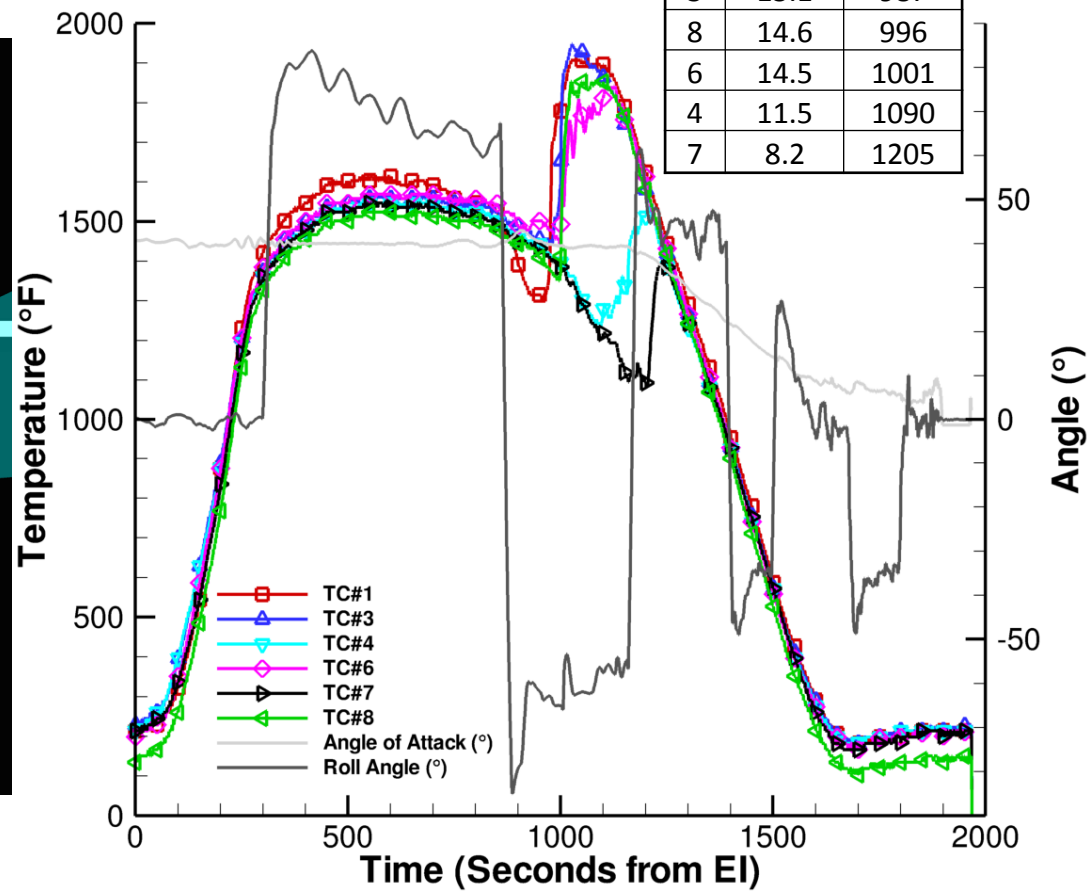




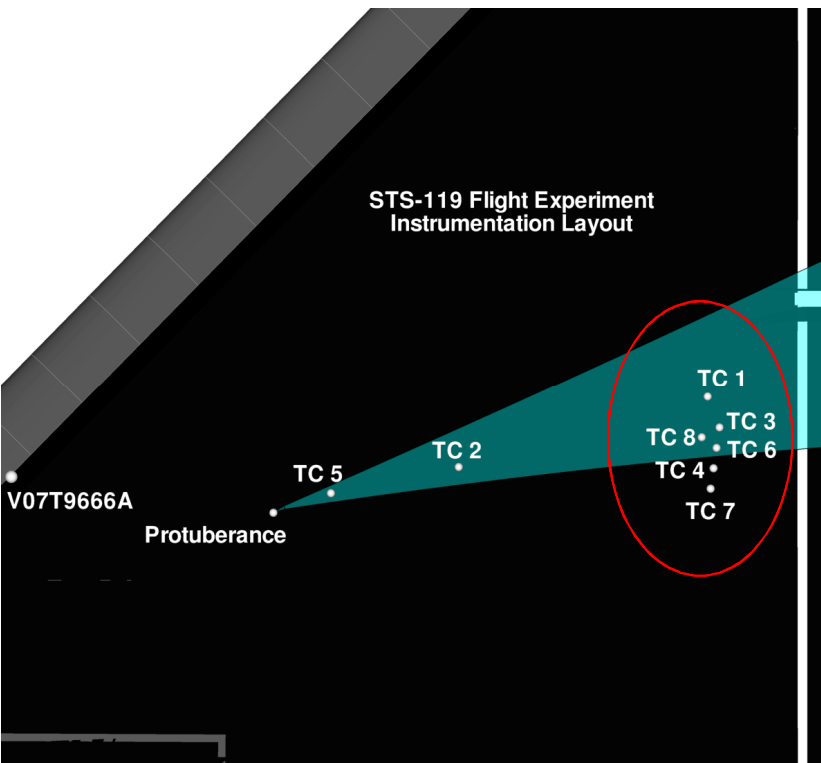
STS-119 BLT FE Data



TC	Mach	Time (s)
1	15.6	969
3	15.1	987
8	14.6	996
6	14.5	1001
4	11.5	1090
7	8.2	1205

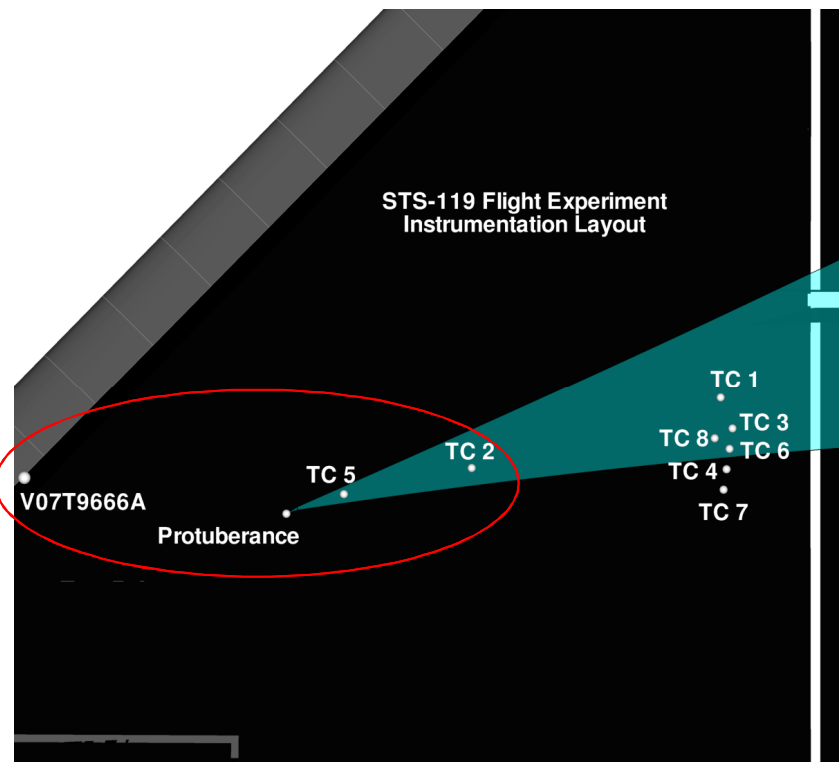


STS-119 Flight Experiment Instrumentation Layout

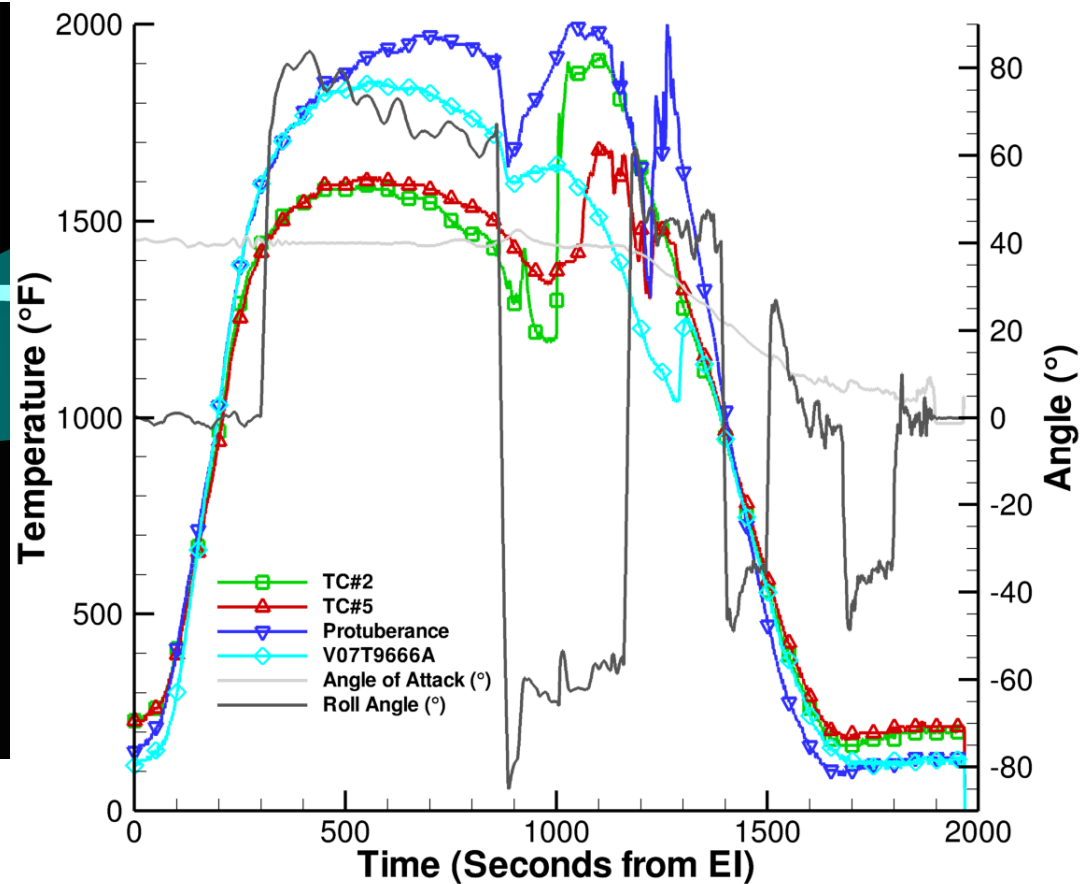




STS-119 BLT FE Data



TC	Mach	Time (s)
2	14.5	1001
5	13.1	1045
Protuberance	7.7	1224
V07T9666A	6.4	1291

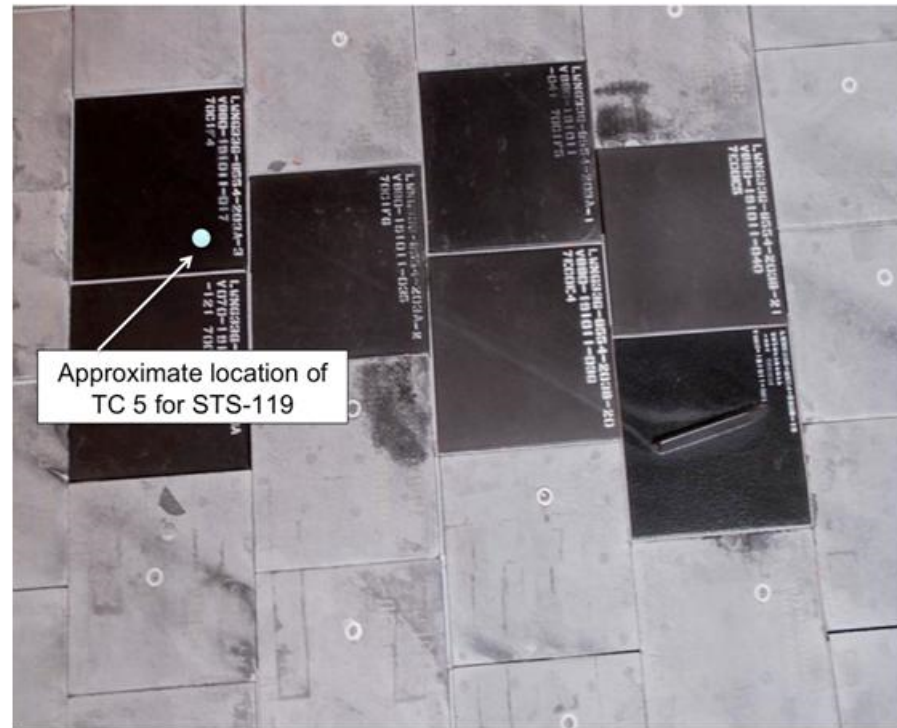




STS-119 Post Flight Observations

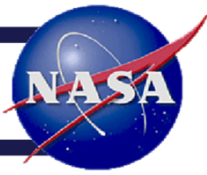


- Earliest BLT onset: Mach 15.6
 - Prediction: Mach 15.4
- Maximum measured protuberance temperature: 2011°F
 - Prediction: ~2900°F
- Temperatures on tile surrounding protuberance did not exceed 2500°F*
 - Prediction: 2720°F
 - Temperatures hypothesized to be much lower than 2500°F
- Half angle: ~7 deg
- Thermocouple 5 moved for STS-128 based on post-flight observations of tile surface deposit





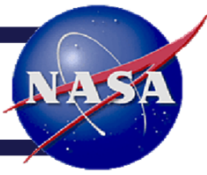
Pre- STS-128 Analysis



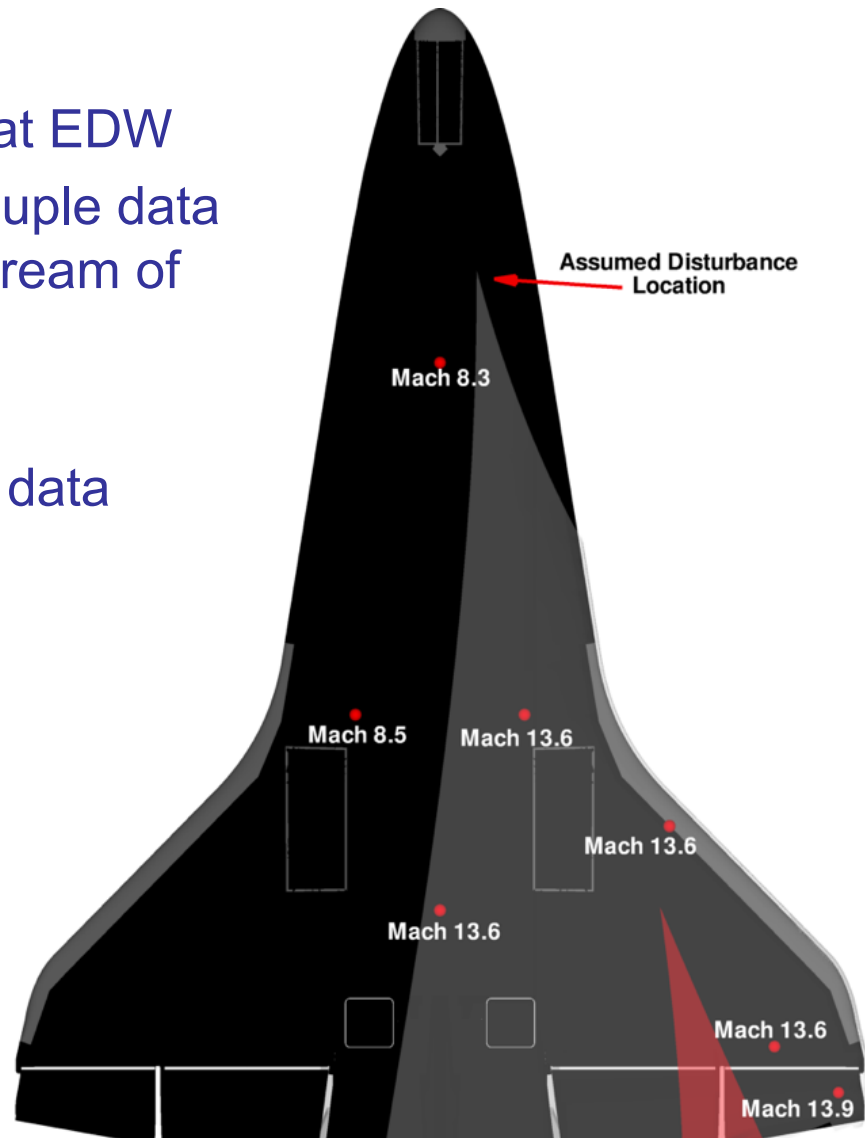
- Cause for temperature over-prediction unknown. Possible explanations:
 - Non-continuum effects
 - Boundary layer profile errors
 - Errors in extent of separation upstream of protrusion
 - Thermal response prediction errors
 - Other ideas?
- Team had ~1 month to review the data, revise models, and perform an adequately rigorous analysis
- Ad-hoc approach developed to force the 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



STS-128 BLT FE Data



- Launched August 29, 2009
- Landed September 11, 2009 at EDW
- Post-flight review of thermocouple data showed asymmetric BLT upstream of flight experiment hardware
- Cause of event unknown
- Event makes interpretation of data challenging

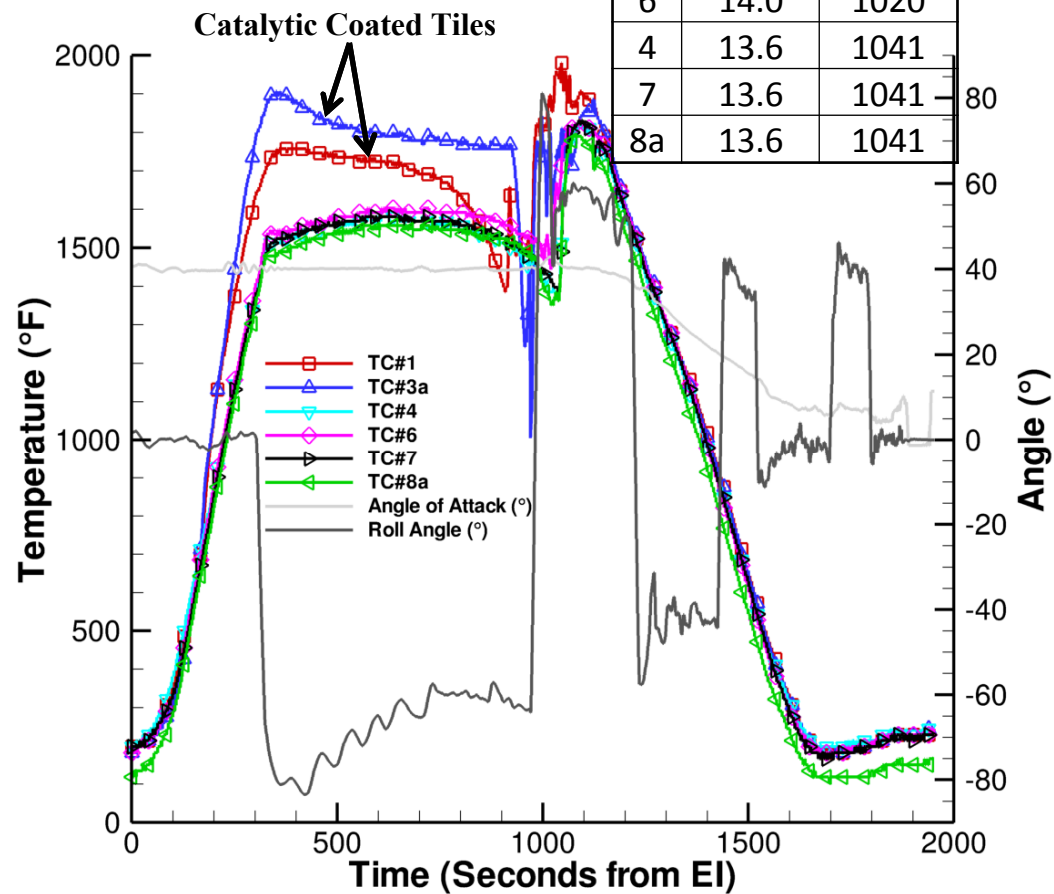




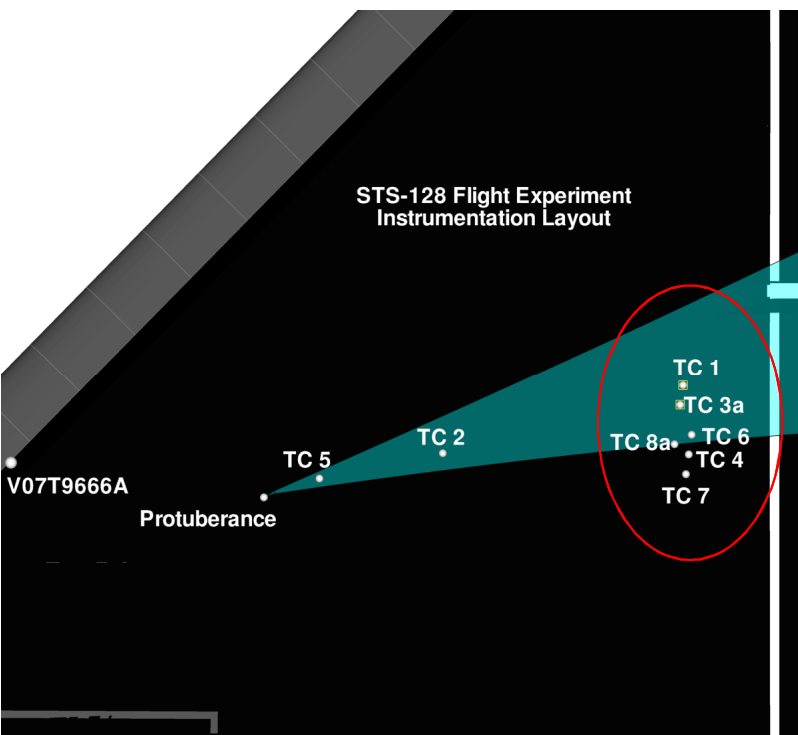
STS-128 BLT FE Data



TC	Mach	Time (s)
1	17.5	913
3a	17.4	925
6	14.0	1020
4	13.6	1041
7	13.6	1041
8a	13.6	1041

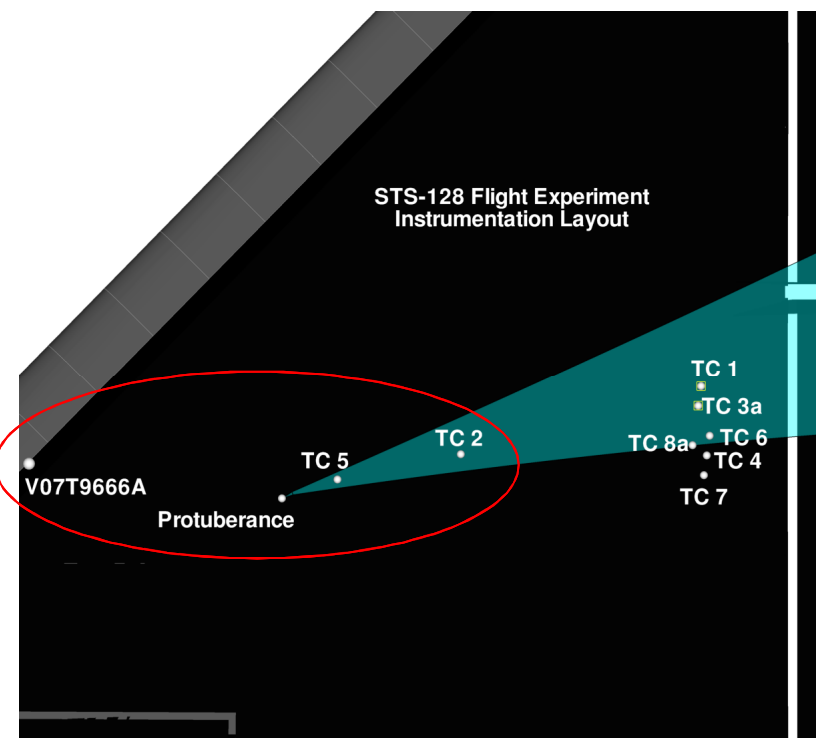


STS-128 Flight Experiment
Instrumentation Layout

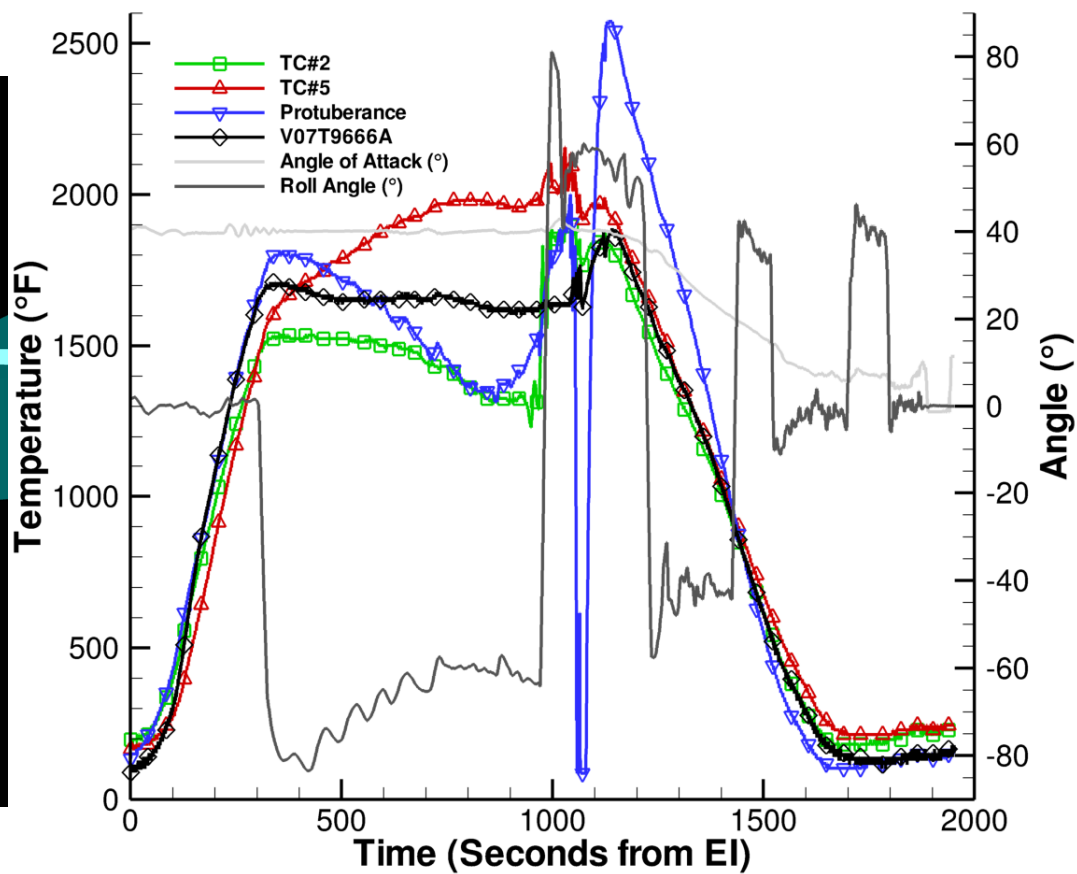




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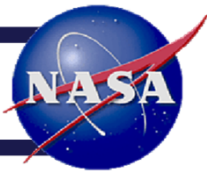


TC	Mach	Time (s)
2	15.5	987
5	14.2	1021
Protuberance	13.6	1041
V0T9666A	13.6	1041

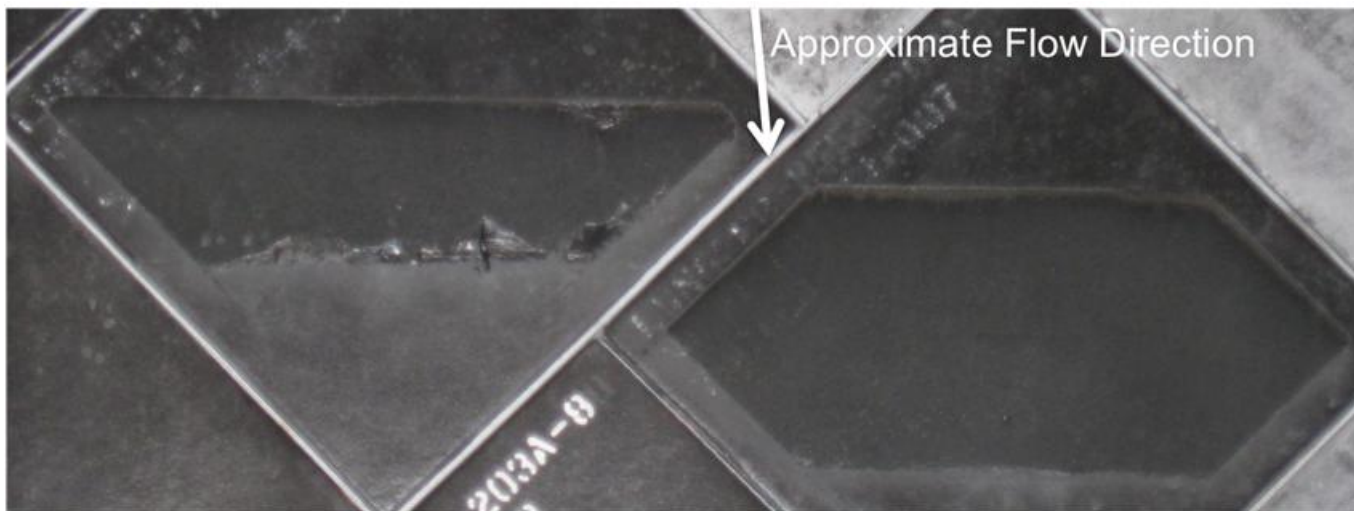




STS-128 Post Flight Observations

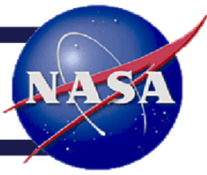


- Earliest BLT onset: Mach 17.5
 - Prediction: Mach 17.4
- Maximum measured protuberance temperature: 2562°F
 - Prediction: ~2800°F
- Temperatures on tile surrounding protuberance did not exceed 2500°F*
 - Prediction: 2995°F
 - Temperatures hypothesized to be lower than 2500°F
- Thermocouple anomaly prevented determination of peak laminar temperature





Pre- STS-131 Analysis



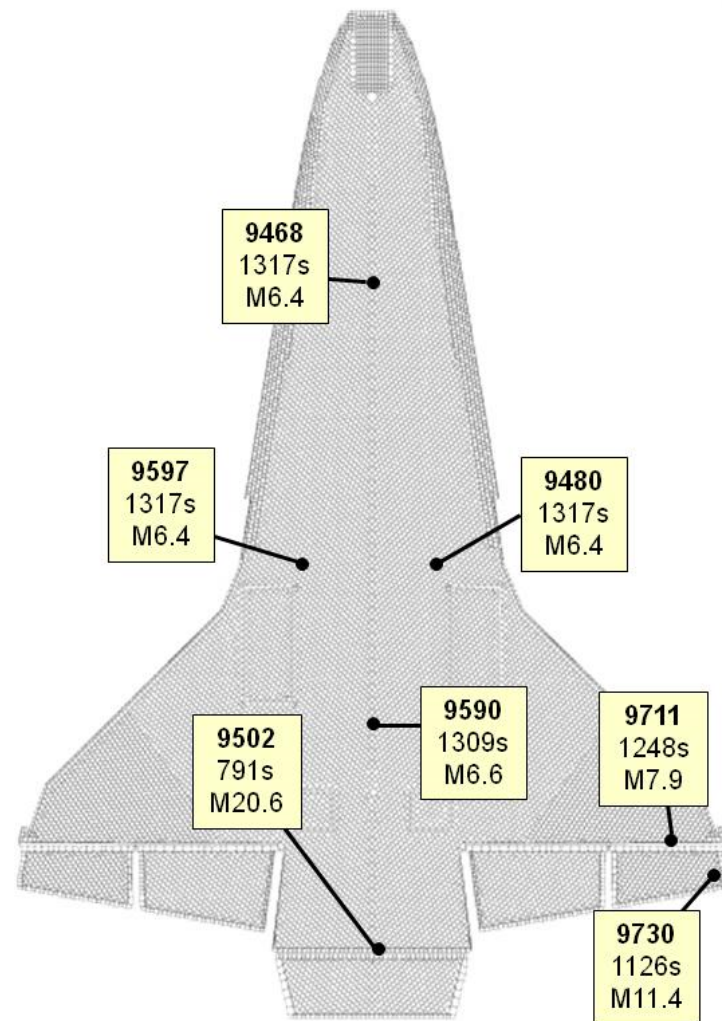
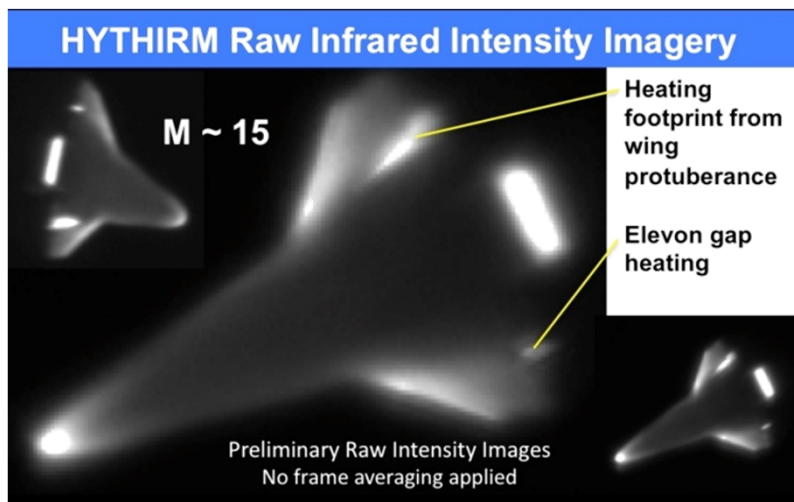
- Cause of thermocouple anomaly unknown - initiation correlated with roll reversal, starts ~350 sec
- Possible causes include:
 - Loose/intermittent MADS wiring - data not consistent with intermittent dropouts, post Flight BLT inspection found nothing wrong with MADS
 - Radio-Frequency coupling with external charged flow field via TC 'antenna' loop
 - Direct voltage and/or current coupling of the TC circuit with the external flow
 - Semi-conductor based Schottky diode effect
- Team decided to re-fly 0.35-inch protuberance
- Catalytic coating to be re-flown on single tile
 - Two thermocouples installed in single tile
 - One placed at beginning of catalytic coating, other in center of tile/coating



STS-131 BLT FE Data

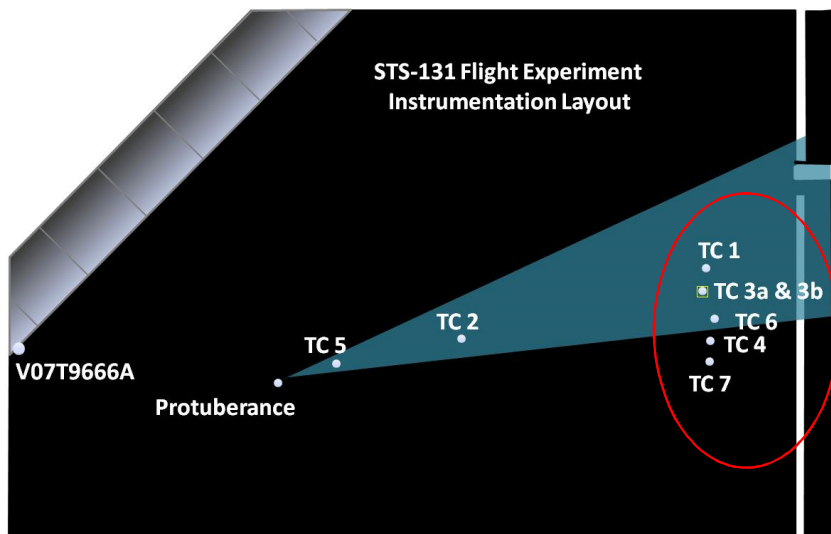
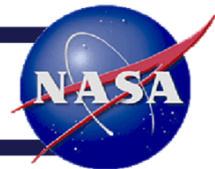


- Launched April 5, 2010
- Landed April 20, 2010 at KSC
- Post-flight review of thermocouple data showed symmetric BLT over vehicle windward surface
- BLT relatively late over windward surface (~Mach 6.4), indicative of vehicle clean of protruding gap fillers, cavities and/or tile-to-tile steps and gaps
- Reflects significant effort of ground crews to prepare vehicle before flight

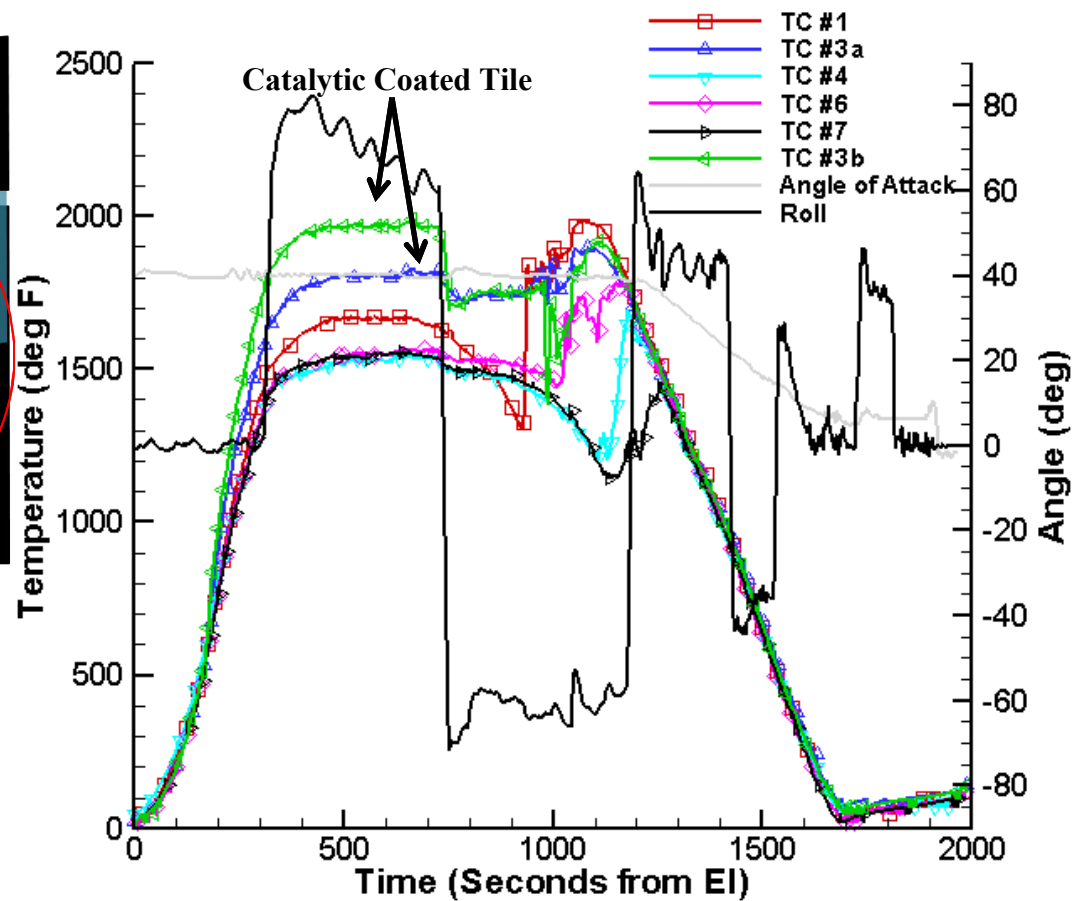




STS-131 BLT FE Data

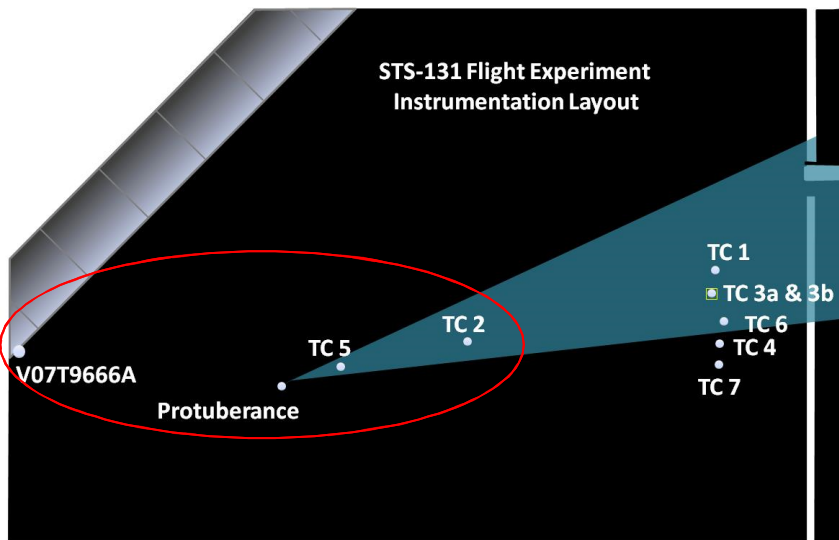
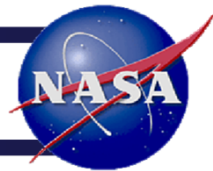


TC	Mach	Time (s)
1	17.4	929
3a	15.1	1012
3b	15.1	1012
6	14.8	1022
4	12.0	1109
7	10.5	1157

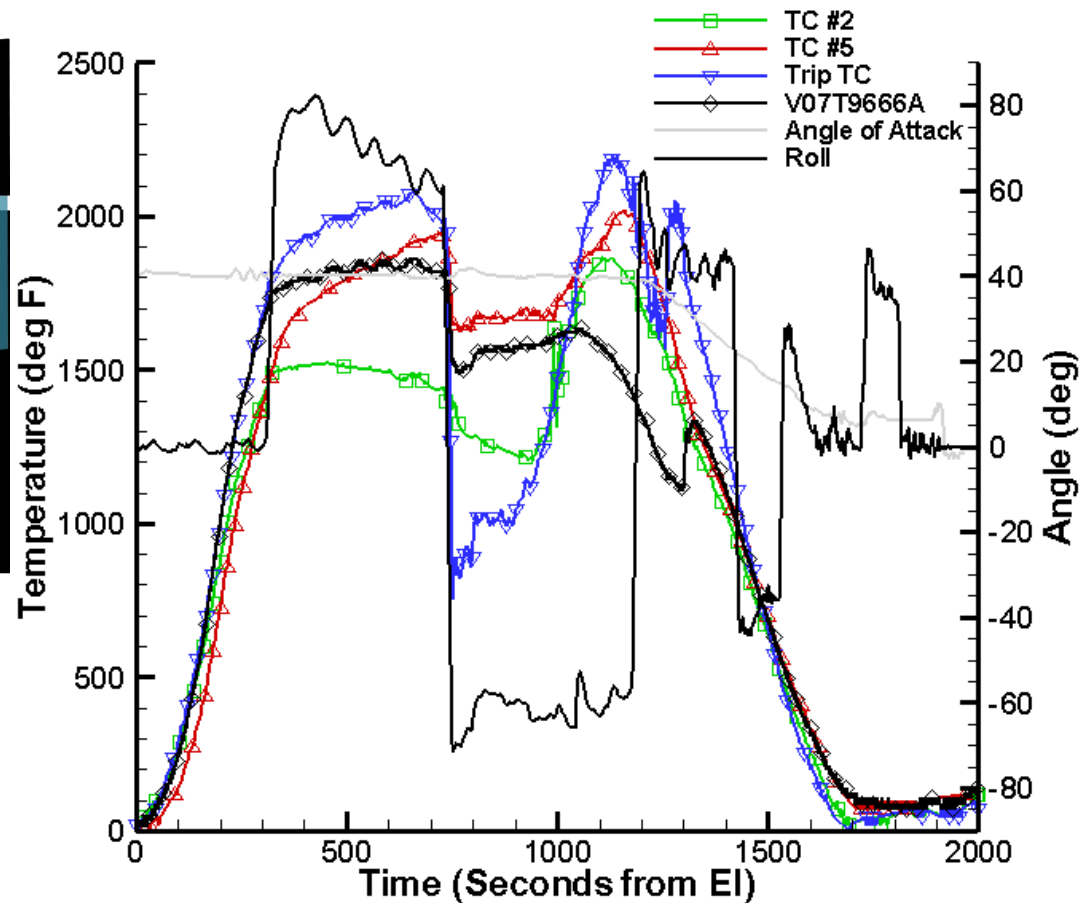




STS-131 BLT FE Data

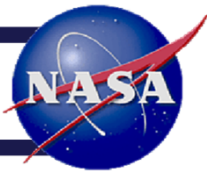


TC	Mach	Time (s)
2	16.9	947
5	15.6	996
Protuberance	7.7	1257
V0T9666A	6.8	1298

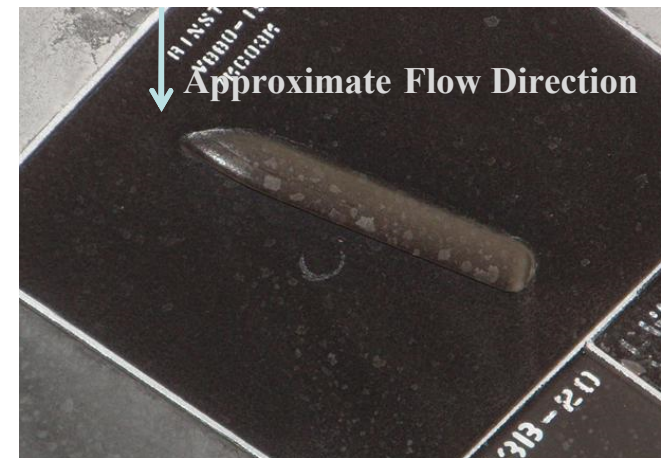
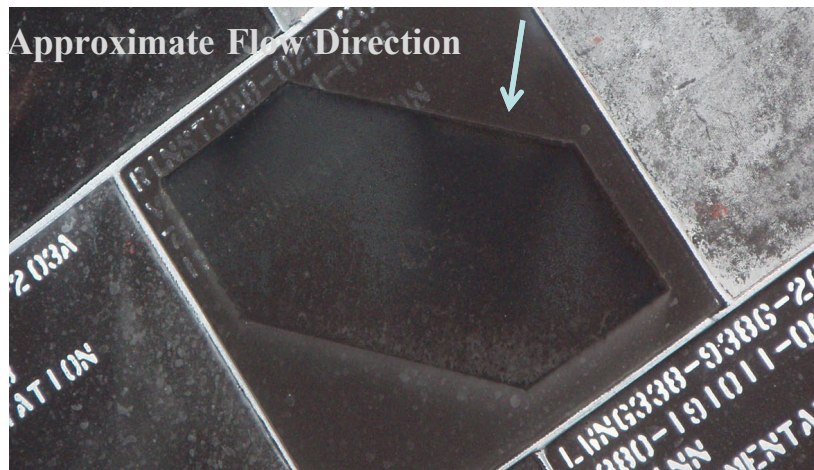




STS-131 Post Flight Observations

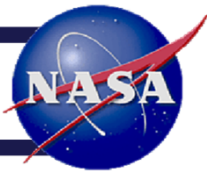


- Earliest BLT onset: Mach 17.4
 - Prediction: Mach 17.2
- Maximum measured protuberance temperature: 2197°F
 - Prediction: ~2650°F
- Temperatures on tile surrounding protuberance did not exceed 2500°F*
 - Prediction: 2925°F
 - Temperatures hypothesized to be lower than 2500°F





Pre- STS-133 Analysis



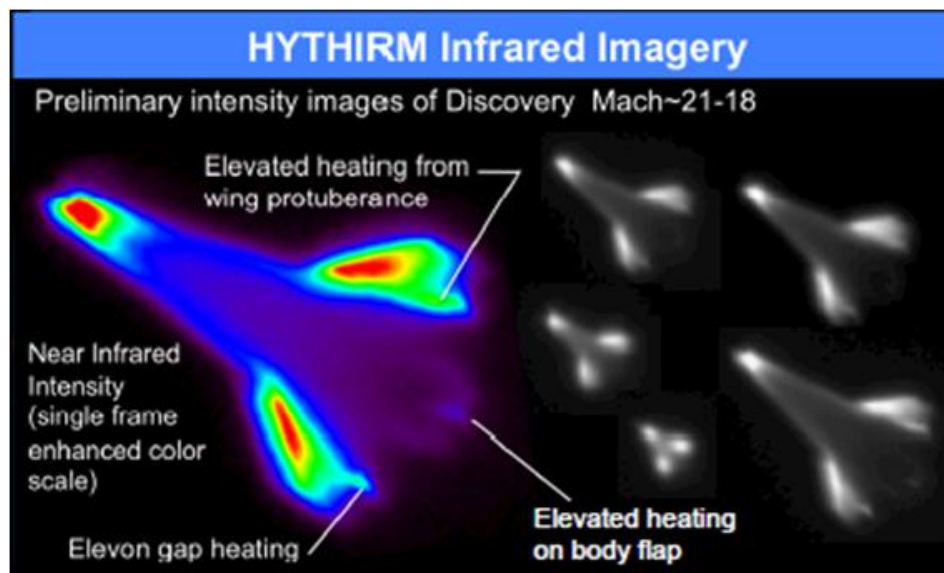
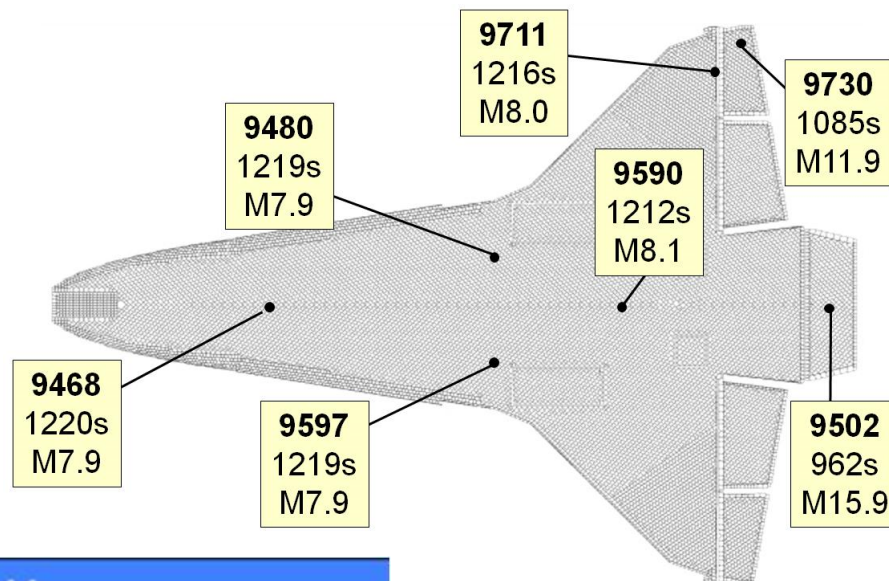
- Team had ~2 month to review data, revise models, perform adequately rigorous analysis
- Knock down factors adjusted to include STS-128 and STS-131 flight data
- Knock down factors applied to STS-133 analysis using CFD solutions for 0.50" protuberance
- 0.5-inch protuberance height results in BLT outside of historical Orbiter experience and required significant discussions with Crew Office.
- Along with STS-133 approval, approval was granted for STS-134 (*Endeavour*) BLT "lite"



STS-133 BLT FE Data

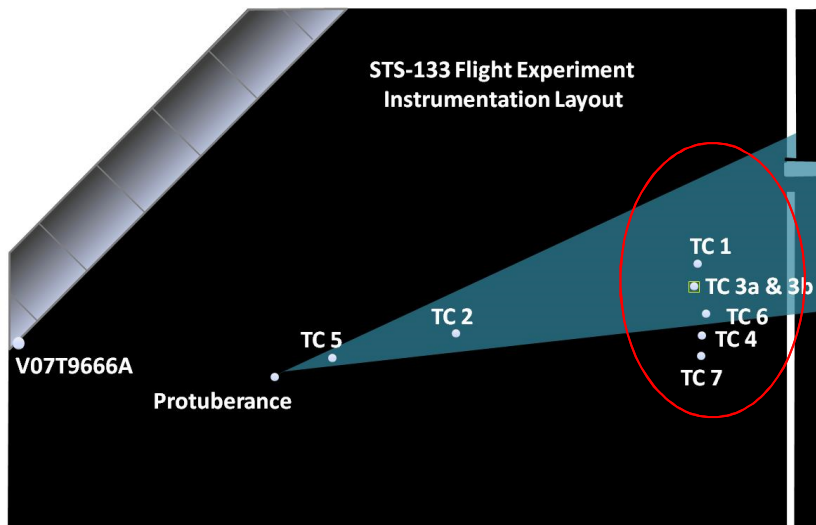
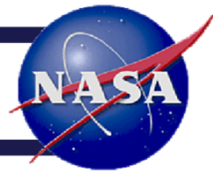


- Launched February 24, 2011
- Landed March 9, 2011 at KSC
- Post-flight review of thermocouple data showed symmetric BLT over vehicle windward surface
- Nominal BLT over windward surface (~Mach 8.1)

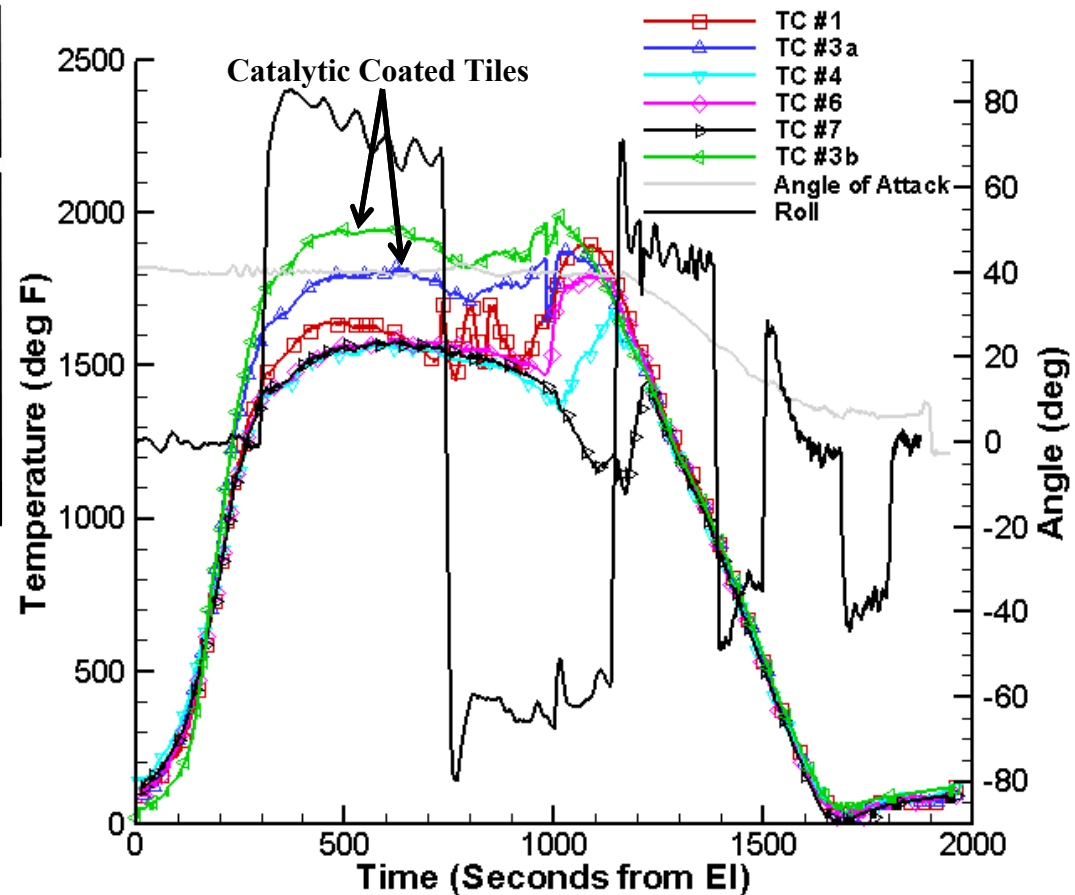




STS-133 BLT FE Data

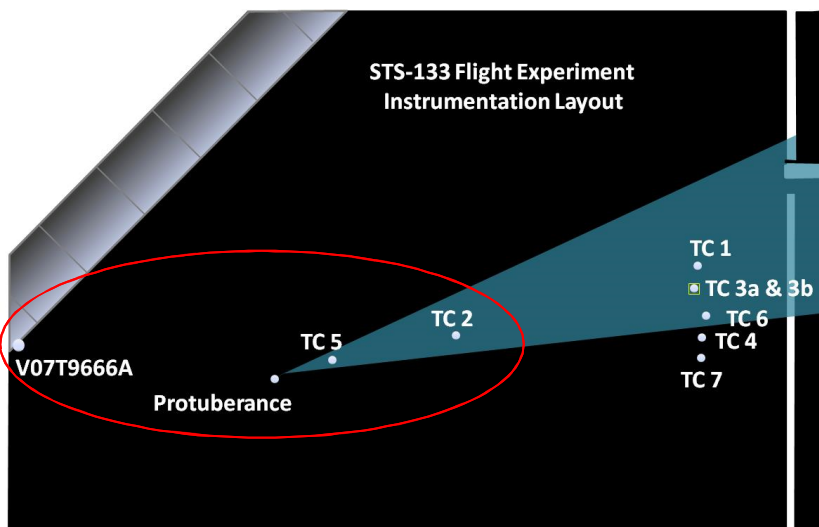


TC	Mach	Time (s)
1	19.6 or 17.3	829 or 916
3b	17.0	925
3a	16.9	929
6	15.4	980
4	14.2	1014
7	11.3 and 9.3	1106 and 1168

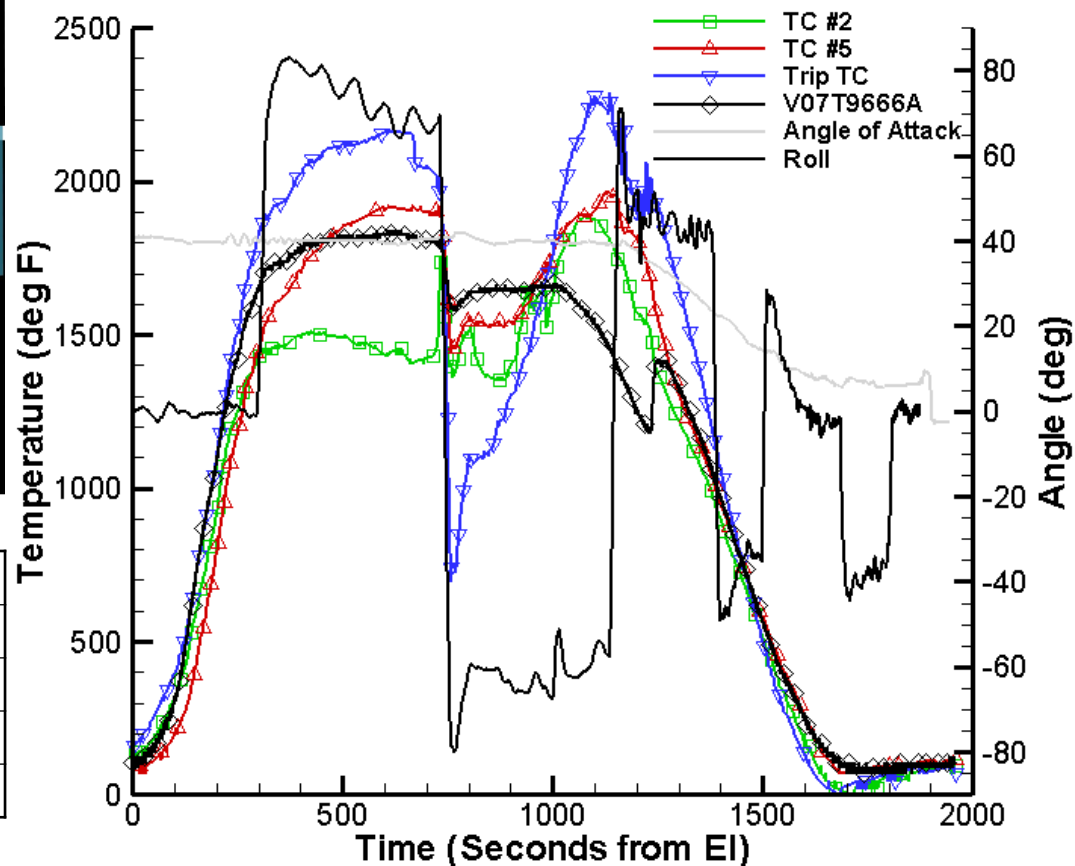




STS-133 BLT FE Data

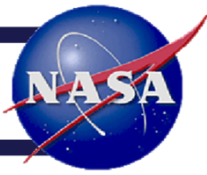


TC	Mach	Time (s)
2	18.1 or 16.2	888 or 953
5	17.6 or 11.9	906 or 1087
Protuberance	8.3	1204
V0T9666A	7.6	1232

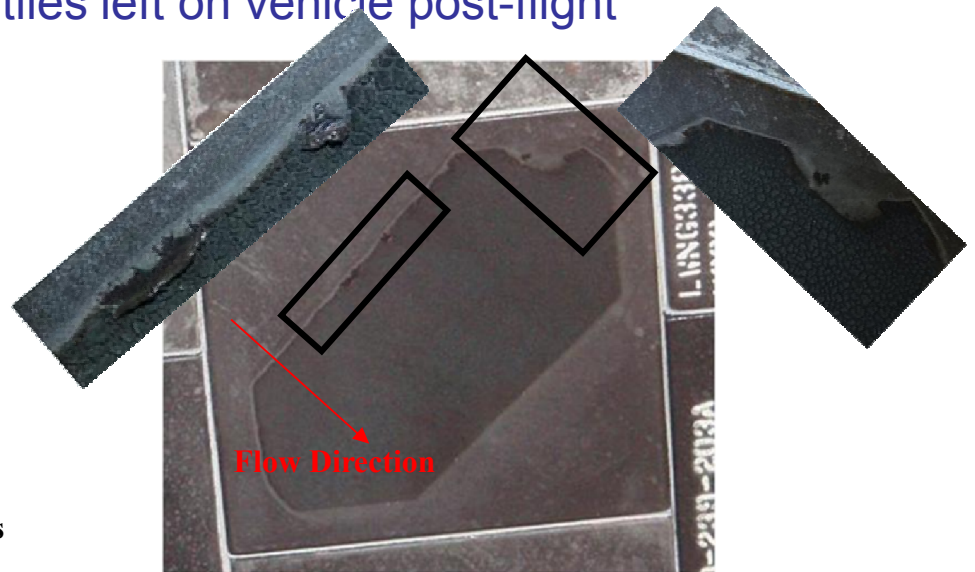
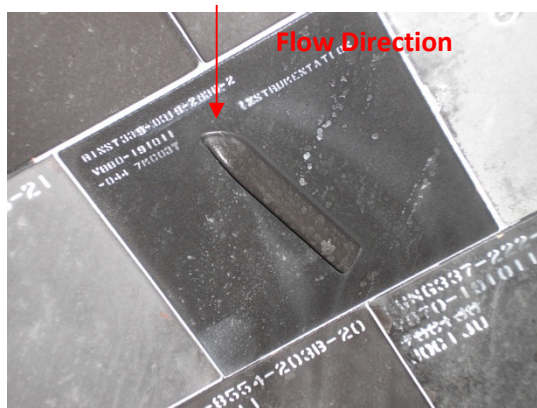




STS-133 Post Flight Observations



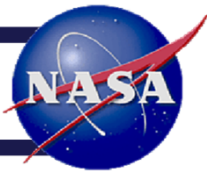
- Earliest BLT onset: Mach 19.6
 - Prediction: Mach 19.2
- Maximum measured protuberance temperature: 2288°F (protuberance BLT Mach 8.3)
 - Prediction: ~2870°F (assumes protuberance BLT at Mach 13.2)
 - Prediction: ~2310°F (assumes protuberance BLT at Mach 8.3)
- Temperatures on tile surrounding protuberance did not exceed 2500°F*
 - Prediction: 2384°F
 - Temperatures hypothesized to be lower than 2500°F
- Protuberance and catalytic coating tiles left on vehicle post-flight



*Based on tile coating inspections

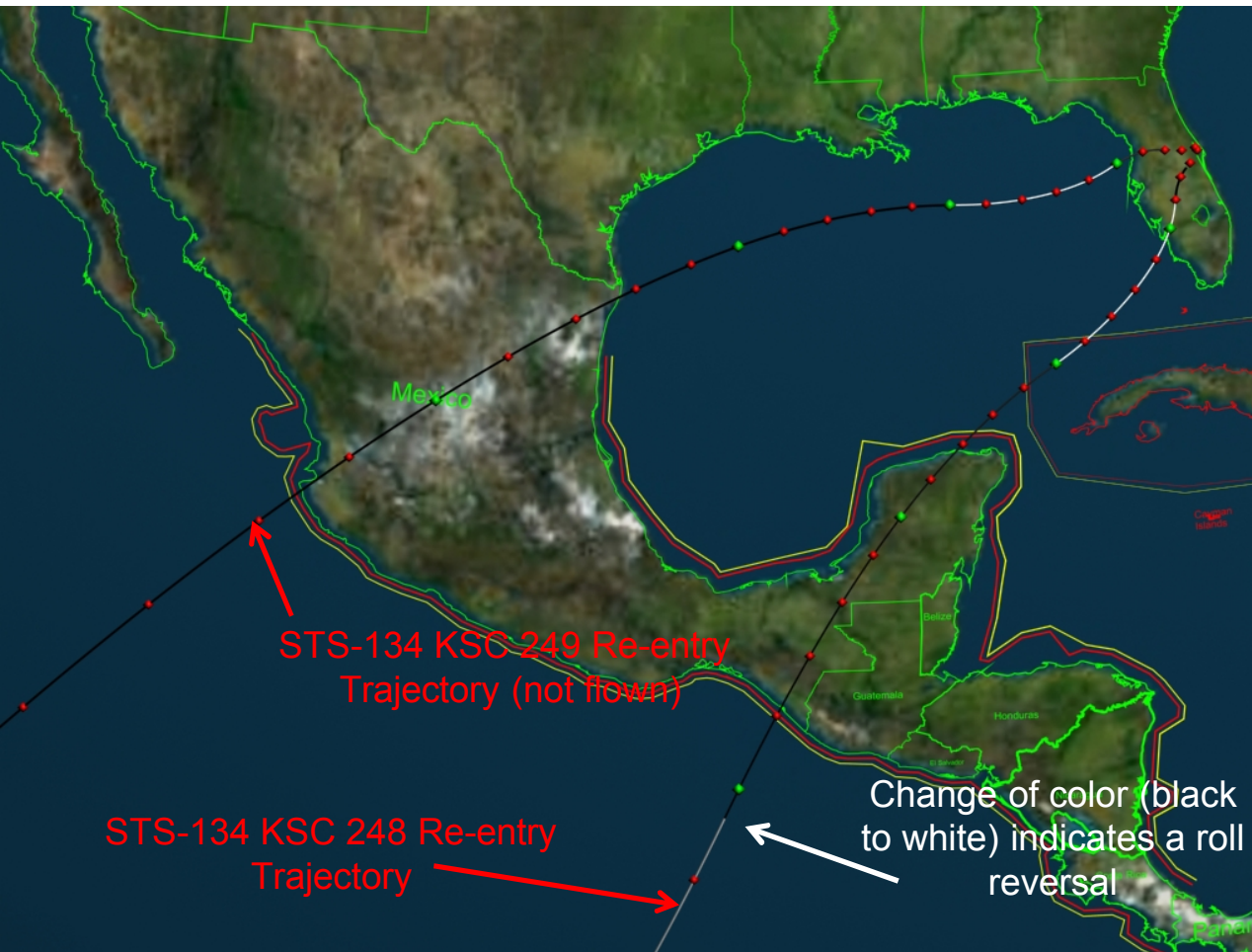


Hypothesis Discussion



- A. BLT *cannot* be initiated with a discrete protuberance at hypersonic non-equilibrium entry conditions.
- B. There *is not* a ground to flight environment scaling effect on discrete protuberance induced BLT at hypersonic non-equilibrium conditions.
- C. High Mach number/high enthalpy non-laminar heating is *not* fully turbulent.
- D. High Mach number/high enthalpy heating for turbulent boundary layers and surface catalysis interact and are thus *dependent* upon each other.

BLT FE Flight Rule to Delay Roll Reversals



- Flight rule tried to support delaying roll reversals until after Mach 16
- Flight rule was lowest priority landing flight rule in program decisions and orbit adjust to support BLT FE was not executed on STS-134 due to other requirements
- STS-134 KSC 248 had a roll reversal at ~Mach 20.5
- STS-134 KSC 249 would have met flight rule requirements