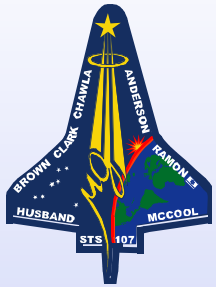

The Columbia Accident: Synopsis of CAIB Report* Regarding the Physical Cause of the Accident and and Personal Thoughts

James O. Arnold, Ph.D

University of California at Santa Cruz
NASA Ames IPA
Investigator, CAIB, Engineering Group 3

***Seminar based on CAIB Appendix F2, Vol IV by J. O. Arnold, H. E. Goldstein and D. J. Rigali**

September 27, 2011

The Board

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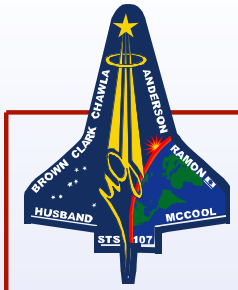
Physical Cause



Aerodynamic

Aerothermodynamic

Sensor Data Timeline

Debris Reconstruction

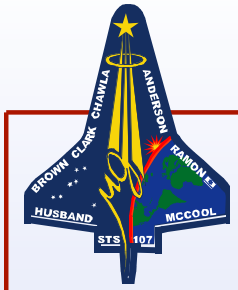
Imaging

Accident Scenario

Impact Test

Physical Cause Statement

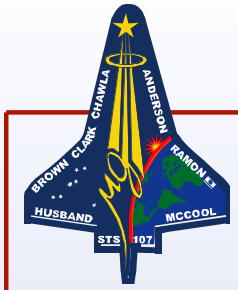
Assignment: “Follow the TPS”



• Confirm or Refute: “During the launch of STS 107, a briefcase-sized piece of foam from the External Tank struck the Reinforced Carbon-Carbon (RCC) Left Wing Leading edge of Shuttle Columbia compromising the RCC. During entry, the damage to the RCC led to the structural failure of the wing, the tragic loss of Columbia and the STS 107 crew”

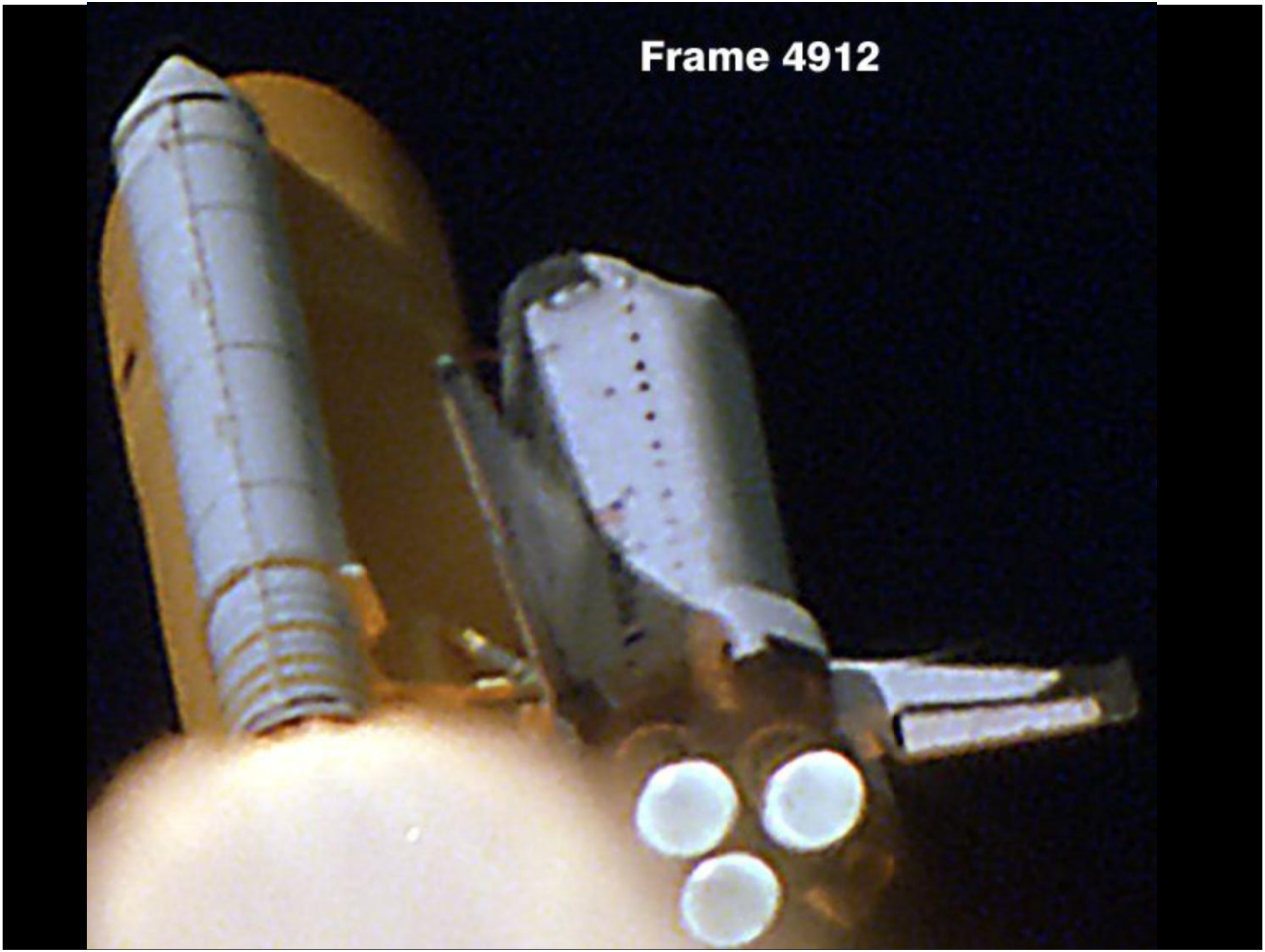
• This was the first, obvious loss of any U.S. vehicle during hypervelocity atmospheric entry, greatly complicating the investigation.

• CAIB board member, G. Scott Hubbard assigned the “Follow the TPS” task to J. O. Arnold, H.E. Goldstein and D. J. Rigali on February 6, 2003, less than a week after the accident. The results were published in August, 2003.



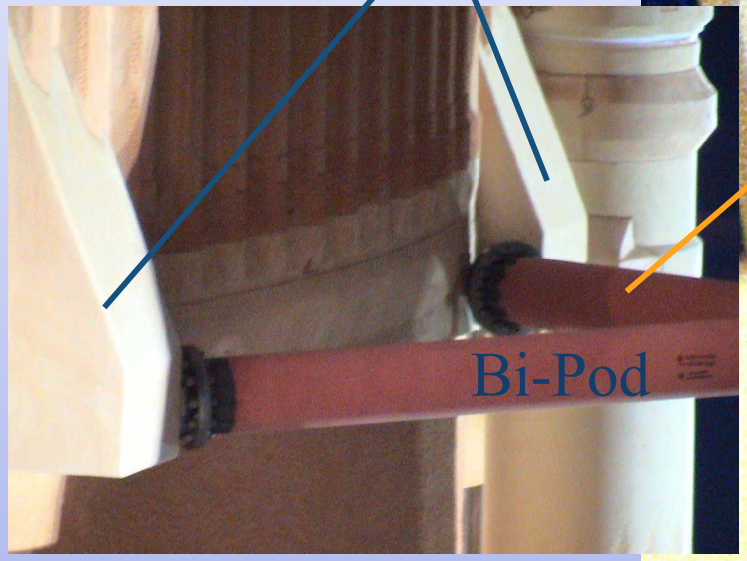
What did we know early in the investigation?

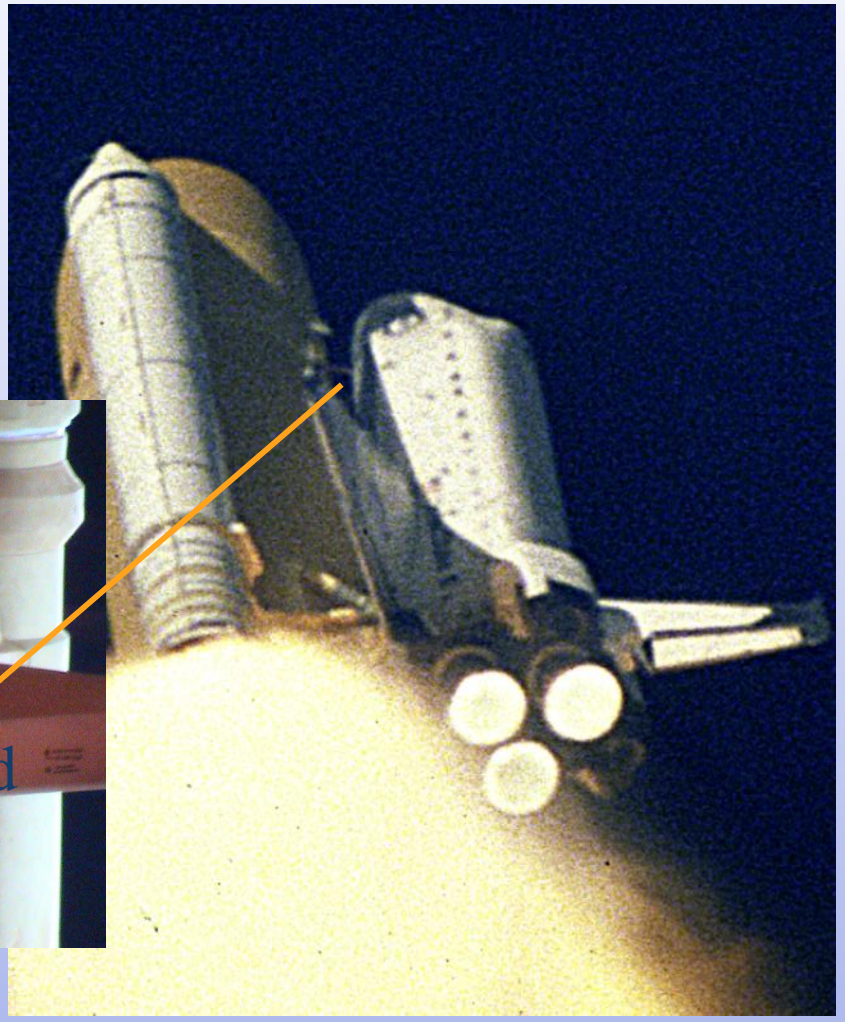
- Combined background in aerothermodynamics, Shuttle tiles and carbon-carbon
- Knowledge that superheated shock layer gases had entered the left wing box, very probably melting the aluminum substructure, and in essence, sawing the left wing off from the inside-out.
- Very poor quality imagery of the foam strike - no underside view
- Amateur video of entry from California coastline to Texas, including the Starfire photograph taken in New Mexico
- NASA data tracking, but No Orbiter Experiments (OEX) on-board engineering data - this was stored on board on magnetic tape and subsequently was recovered.


Frame 4912

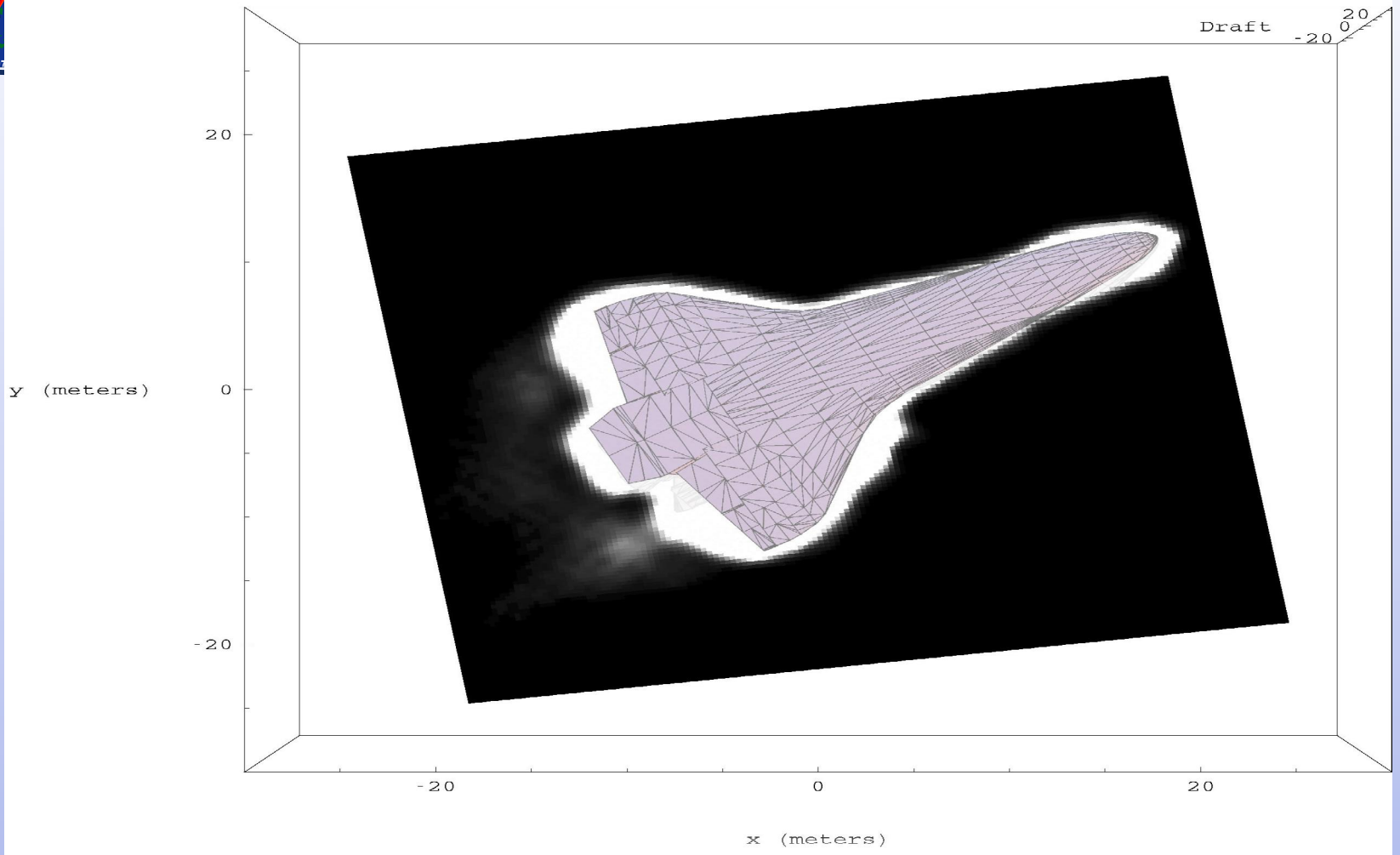
STS-107

Bi-Pod Ramps





Starfire Photo from Kirtland AFB GMT13:57:14



Starfire Optical Range Image (26 March 2003)
model overlay (R. Cleis, R. Fugate, R. Johnson)
image sharpened using deconvolution (J. Christou)

The model scaling and orientation are based on telemtery (latitude, longitude, and altitude from NASA) and observations (azimuth, elevation, and range from SOR). The image scaling and orientation were derived from measurements using star fields. The Columbia model was provided by NASA.

Background: Shuttle Aerothermodyanmics & TPS

- Entry Trajectory

- Normalized aerothermodynamic entry heating profile

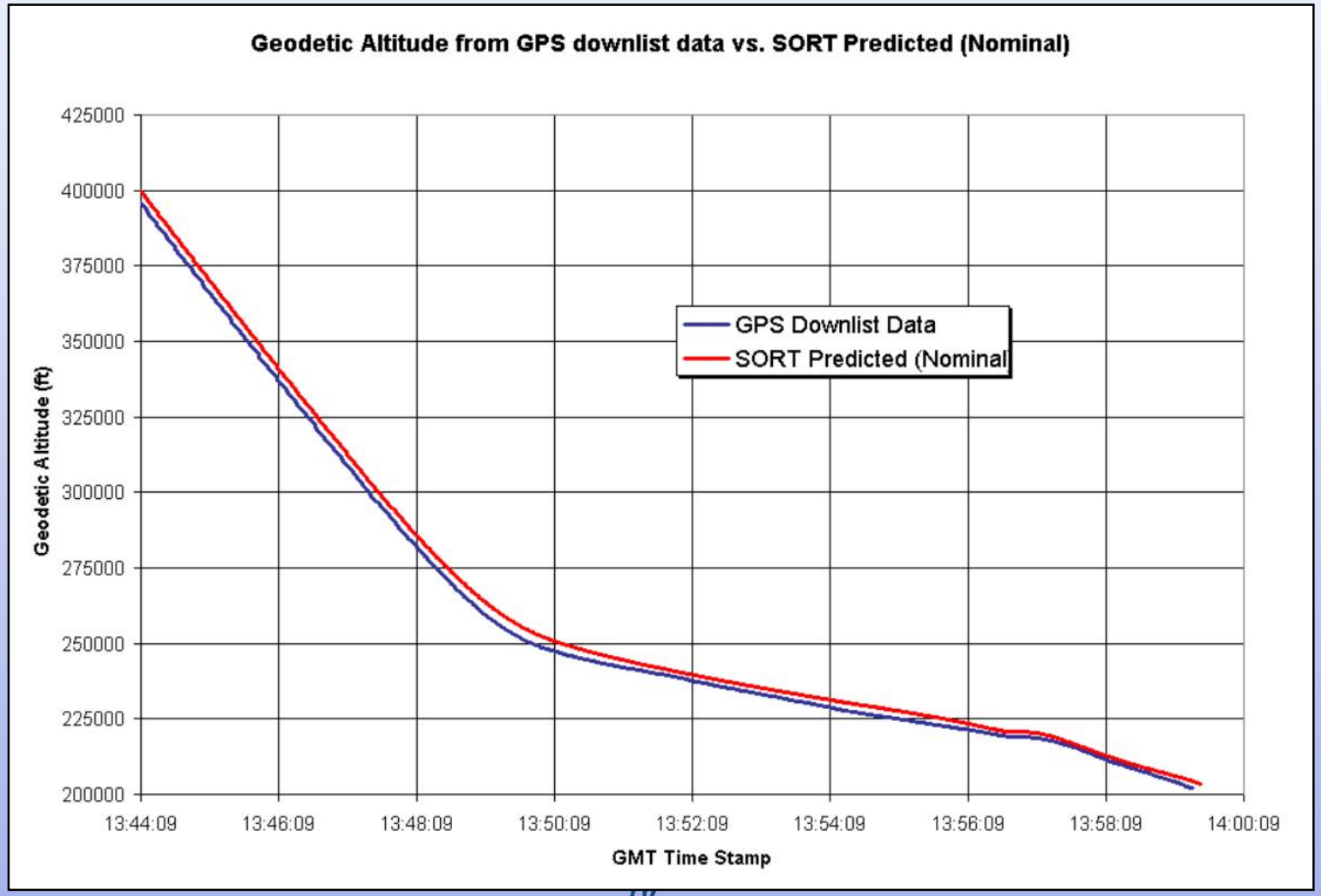
- Zoom-in on wing leading edge

- Space Shuttle Thermal Protection System

- Huge, national efforts in CFD, Thermal Analysis, Aero, etc started soon after the accident, led by NASA JSC

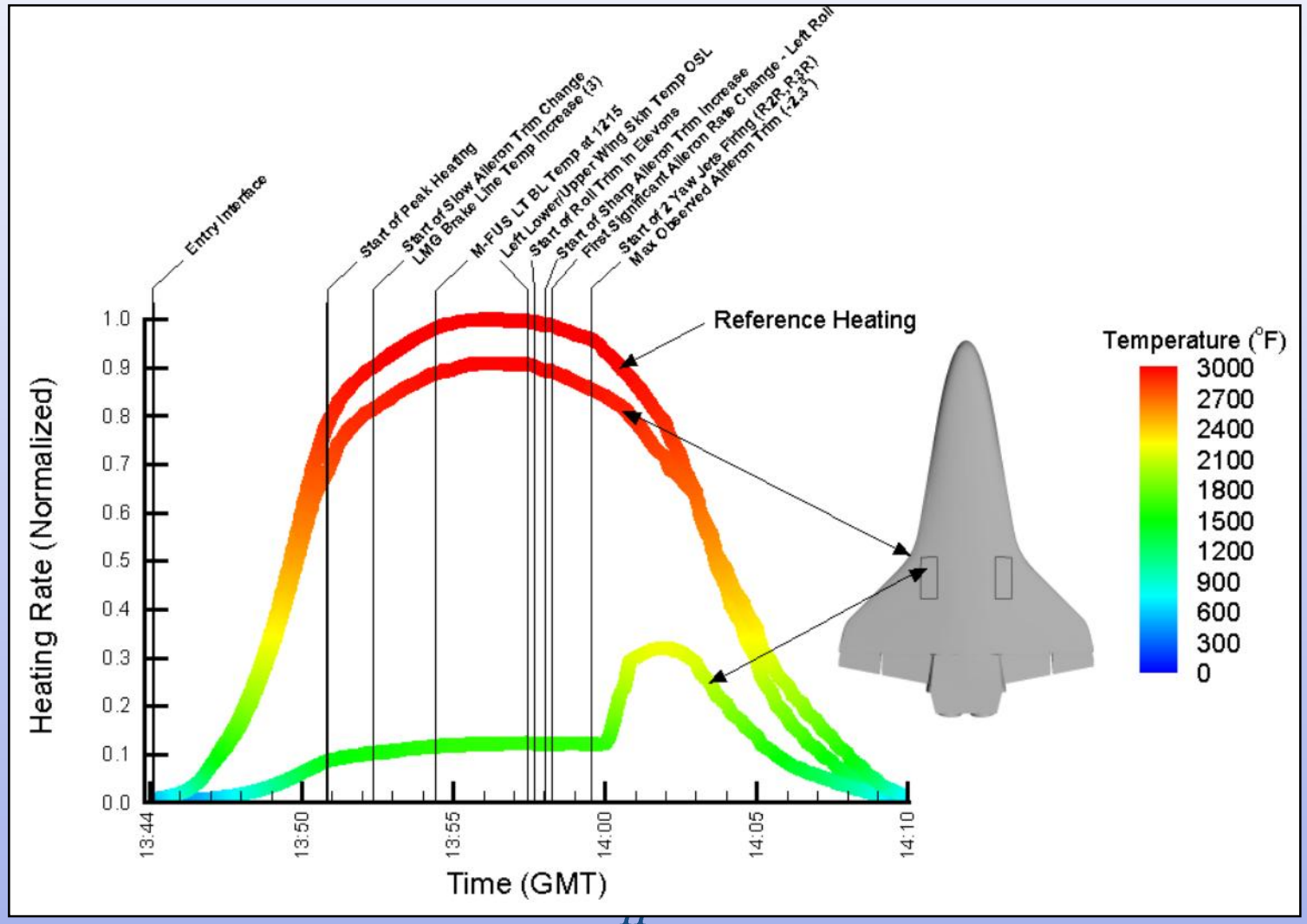
Entry trajectory

Figure 1 (a) Normal entry; Geodetic Altitude Vs
GMT Entry Interface EI
at 400,000 ft/ Mach 24. Angle of attack 40 degrees

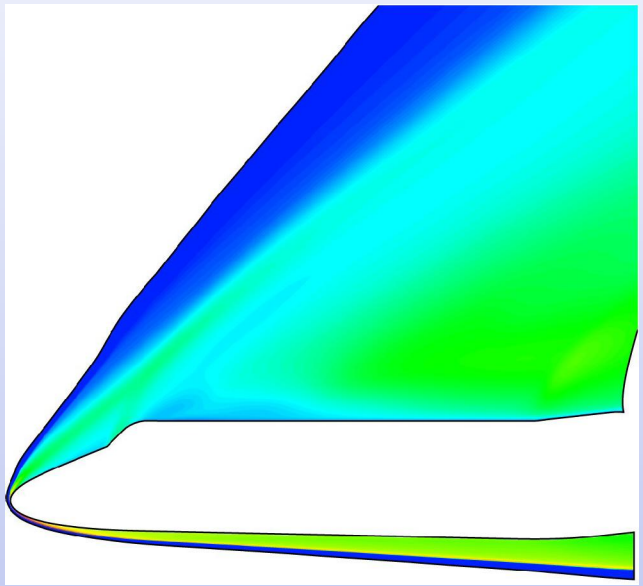


Entry heating

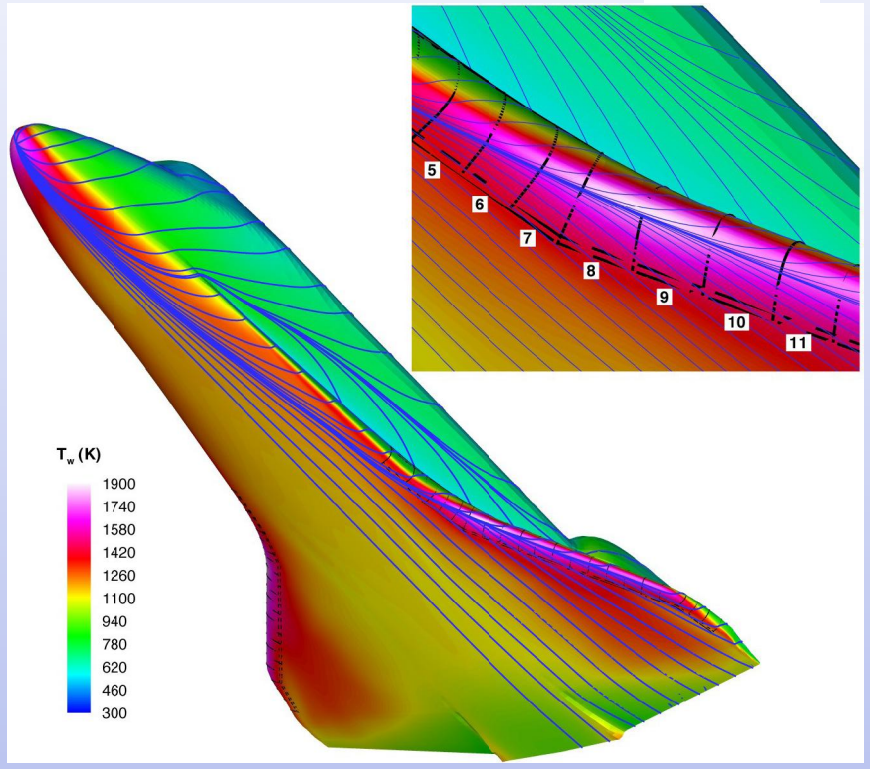
Figure 1 (b) Normal entry; Normalized Heaing Rates Vs
GMT Entry Interface EI
at 400,000 ft/ Mach 24. Angle of attack 40 degrees



Space Shuttle - Bow shock layer and surface temperatures*



Gas Temperatures from CFD Solution
Pitch plane, Near Peak Heating.
Angle of attack: 40 degrees,
246,000 ft altitude, Mach 22.91 at 13:50:53

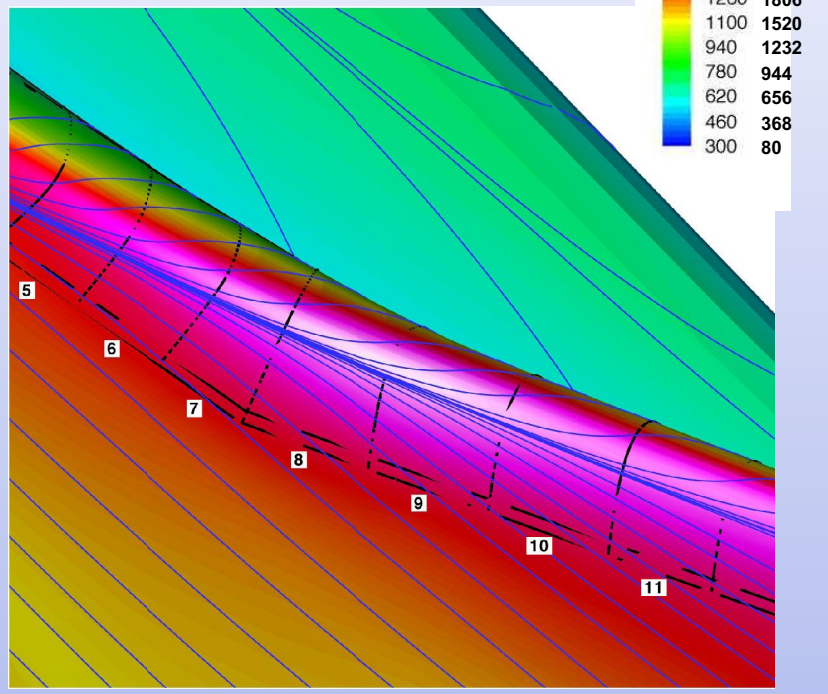


Surface Temperatures from CFD Solution
Near Peak Heating.
Angle of attack: 40 degrees,
246,000 ft altitude, Mach 22.91 at 13:50:53

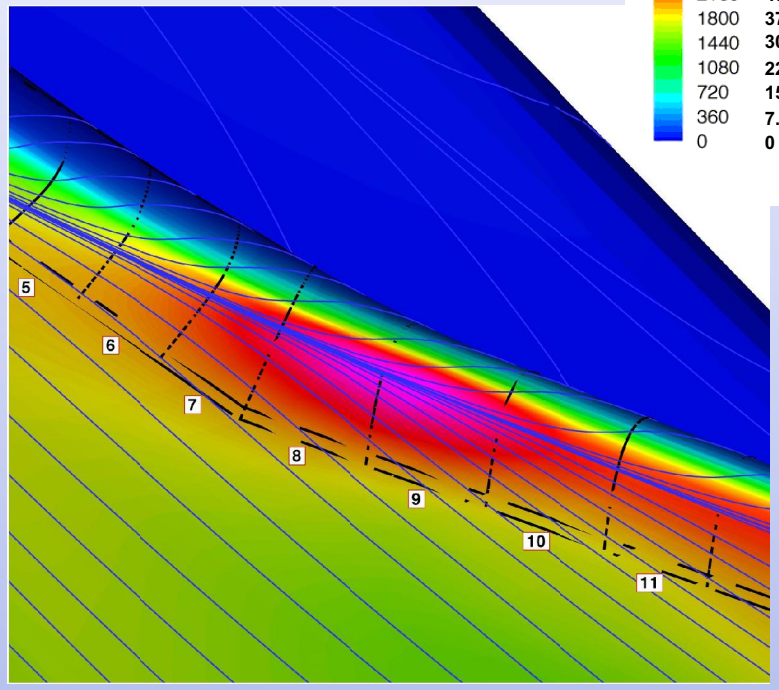
*CFD By NASA Ames, J. Brown, R. McDaniel and D. Prabhu

CFD Solutions for wing leading edge

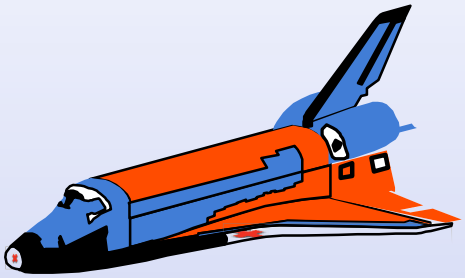
Surface Temperature



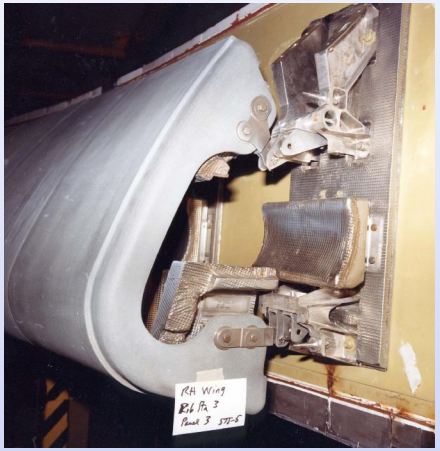
Surface Pressure



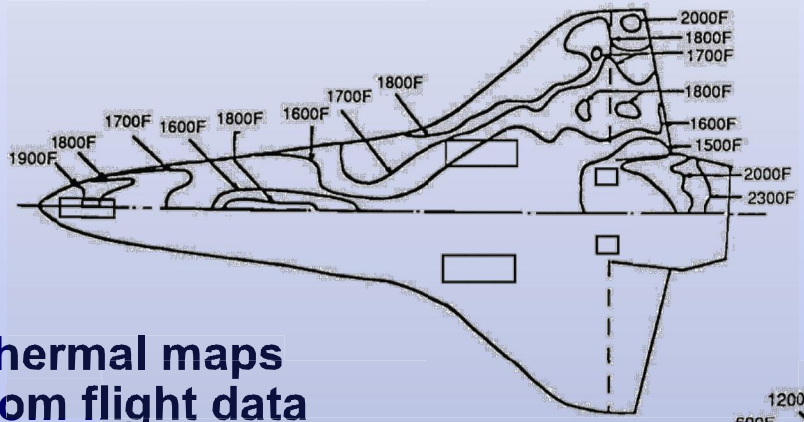
Overview of Space Shuttle TPS

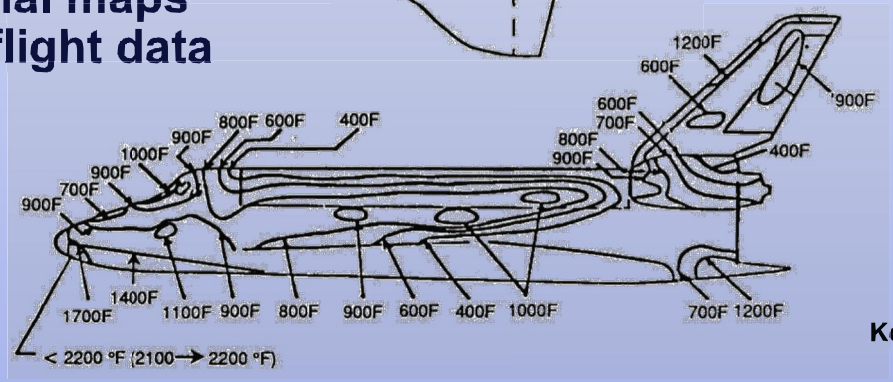


RCC leading edge system



Thermal maps from flight data

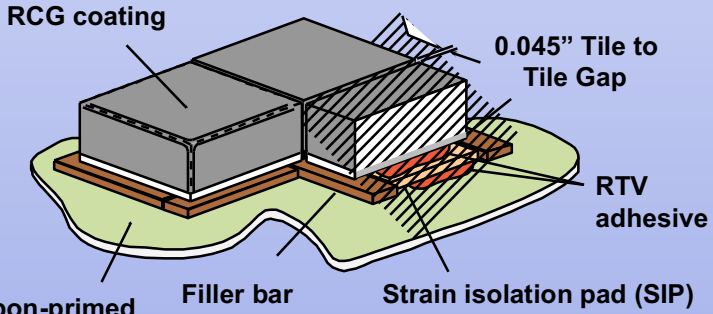


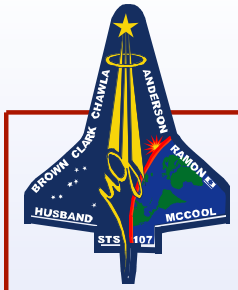


HRSI tile system

- LI-900
- LI-2200
- FRCI-12

Multi-use
Temperature < 2300 F





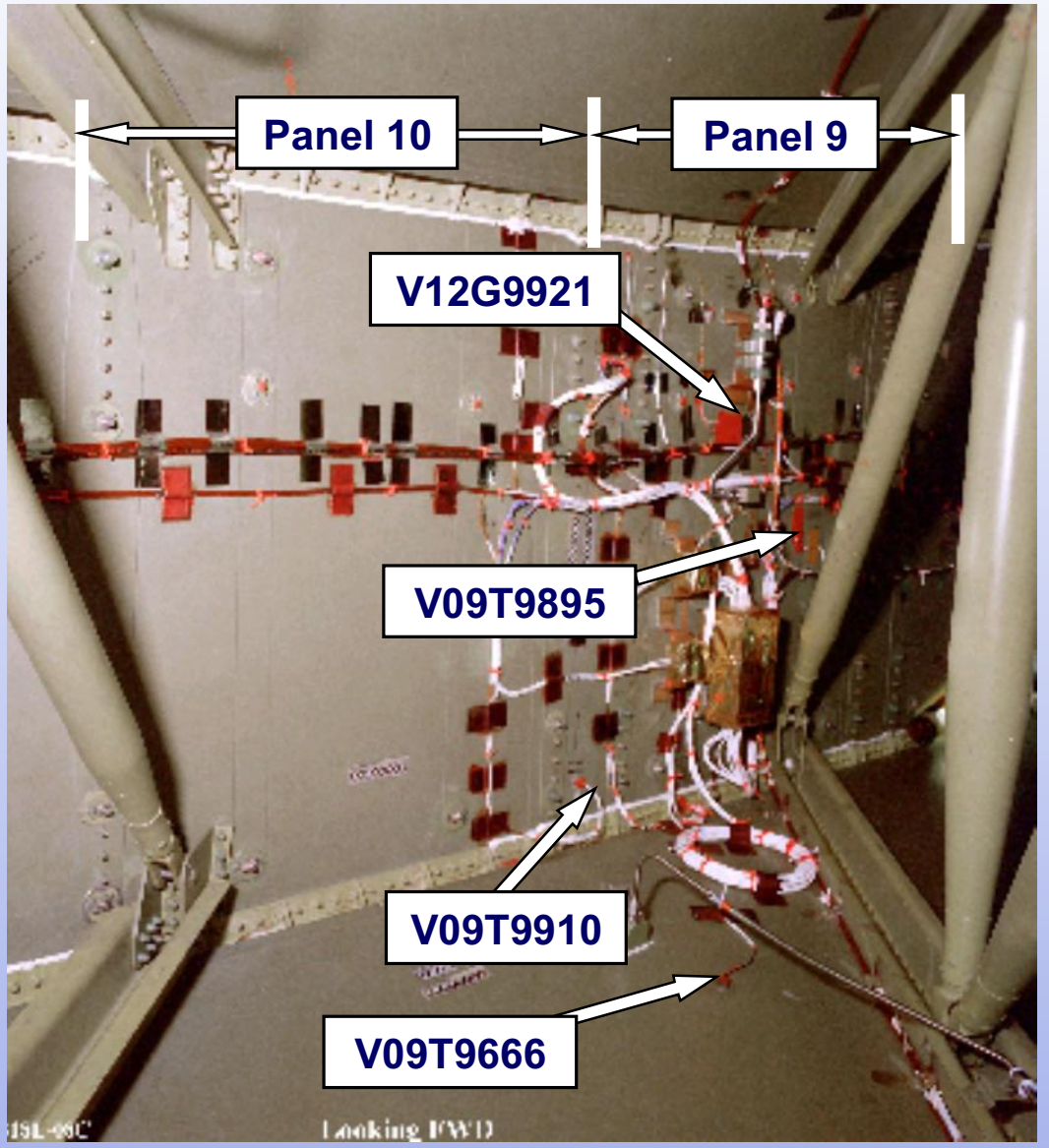
Orbiter Experiments (OEX) sensors and data

• Key Sensors and their locations on the orbiter. Shuttle Columbia was the only vehicle fitted with OEX sensors.

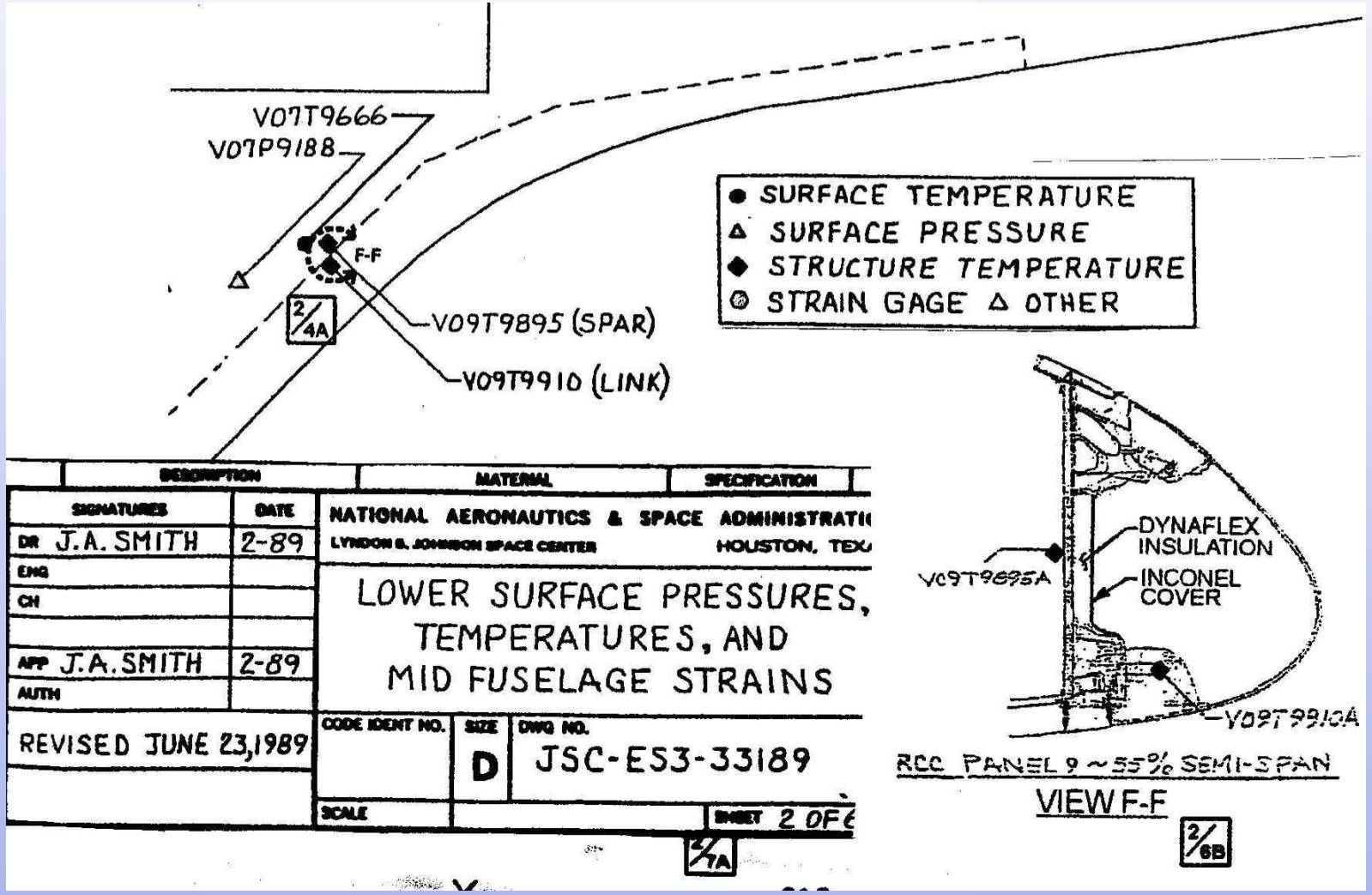
• Out-family sensor readings for STS 107. Tape recorder was recovered from the debris field. By a miracle, the tape was OK.

• Time-line of sensor readings and interpretation

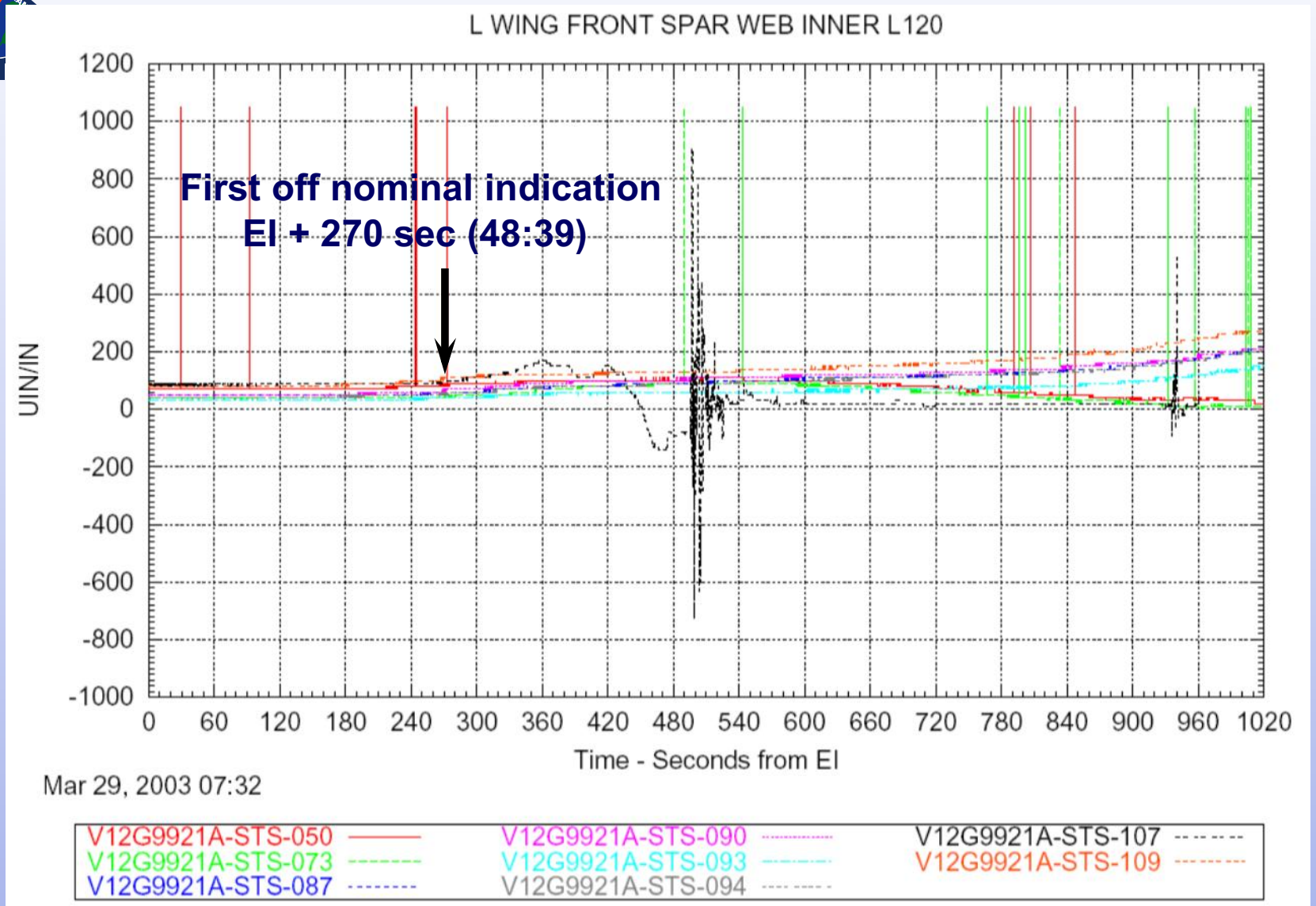
OEX Sensors, inside wing, behind spar



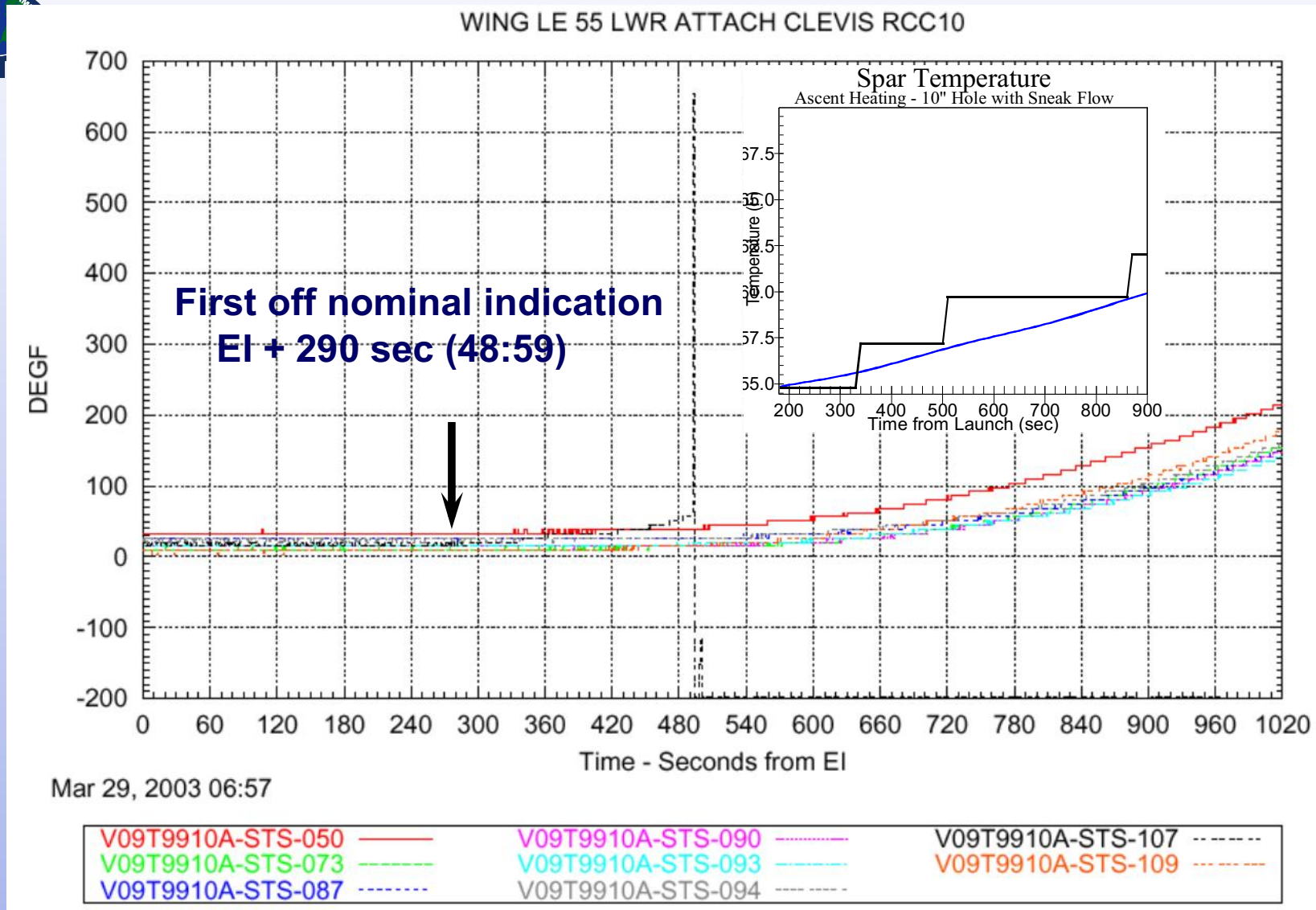
OEX sensor locations



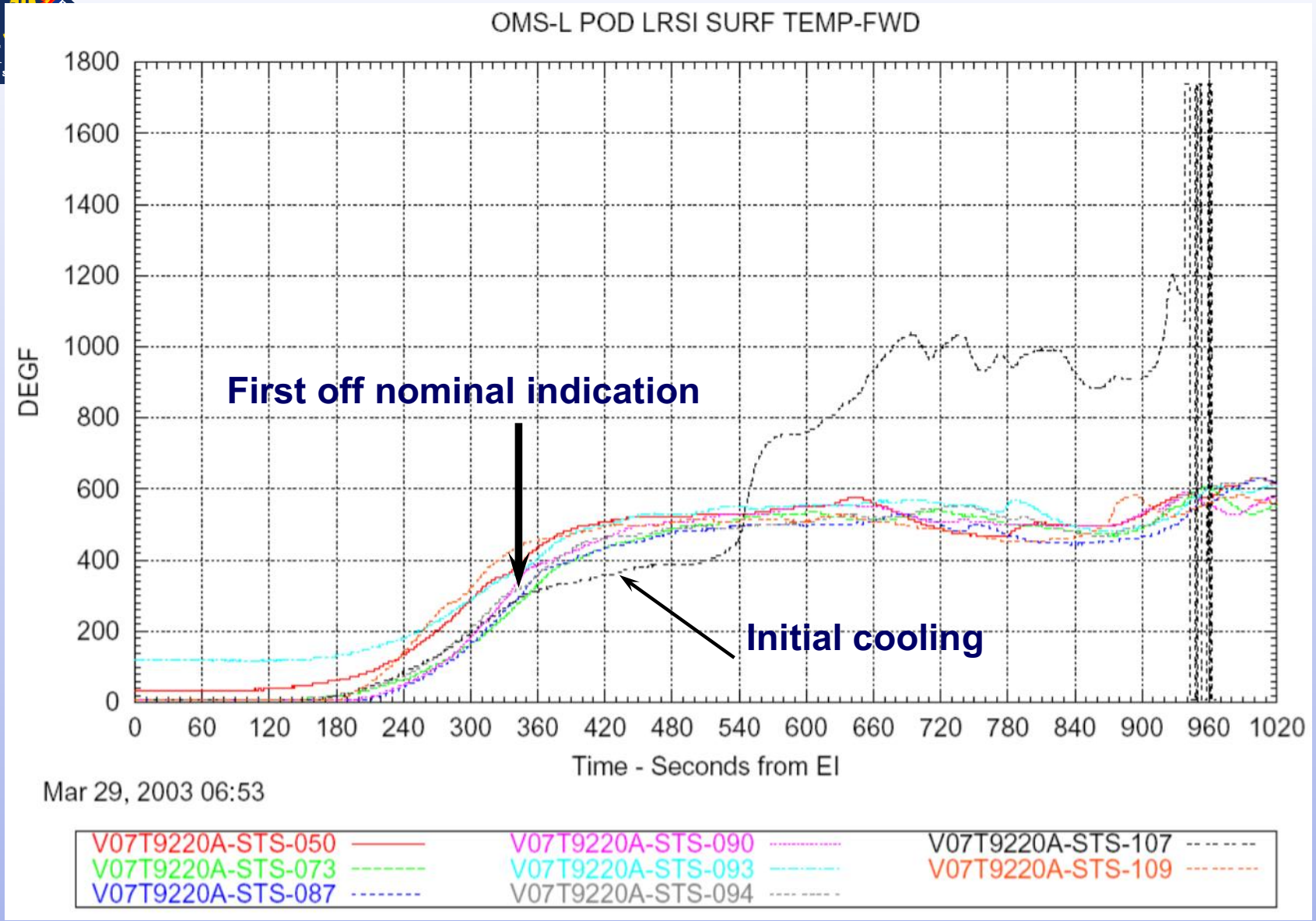
OEX STS-107 Flight Data



OEX STS-107 Flight Data and Thermal Analysis by JSC/C. Madden



"Typical" Off Nominal OMS Pod Temps.

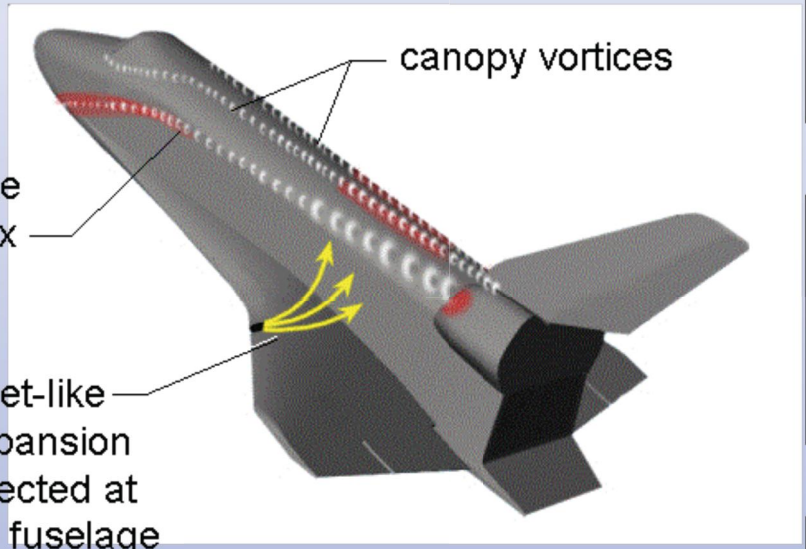


LaRC Wind Tunnel Tests Data help explain cooling trends on OMS pod

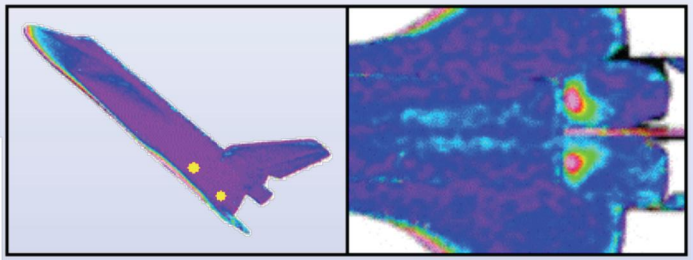
Effect of Missing RCC Panel on Orbiter Leeside Flowfield as Inferred From Surface Heating Patterns

Mach 6 Air $\gamma_{eff} = 1.4$ $\alpha = 40$ deg $Re_{\infty, L} = 2.4 \times 10^6$ $\beta = 0$ deg

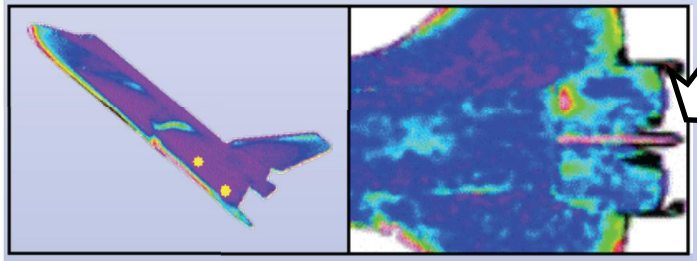
Conceptual sketch of Orbiter leeside flowfield



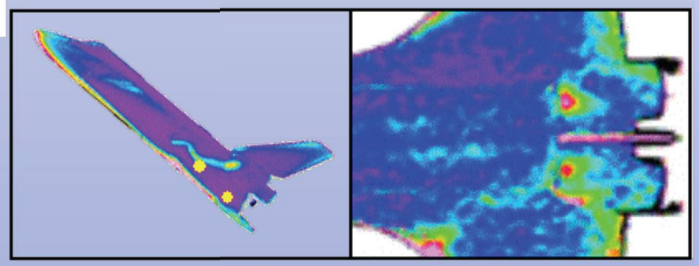
Wing leading edge damage influences leeside flowfield



Baseline

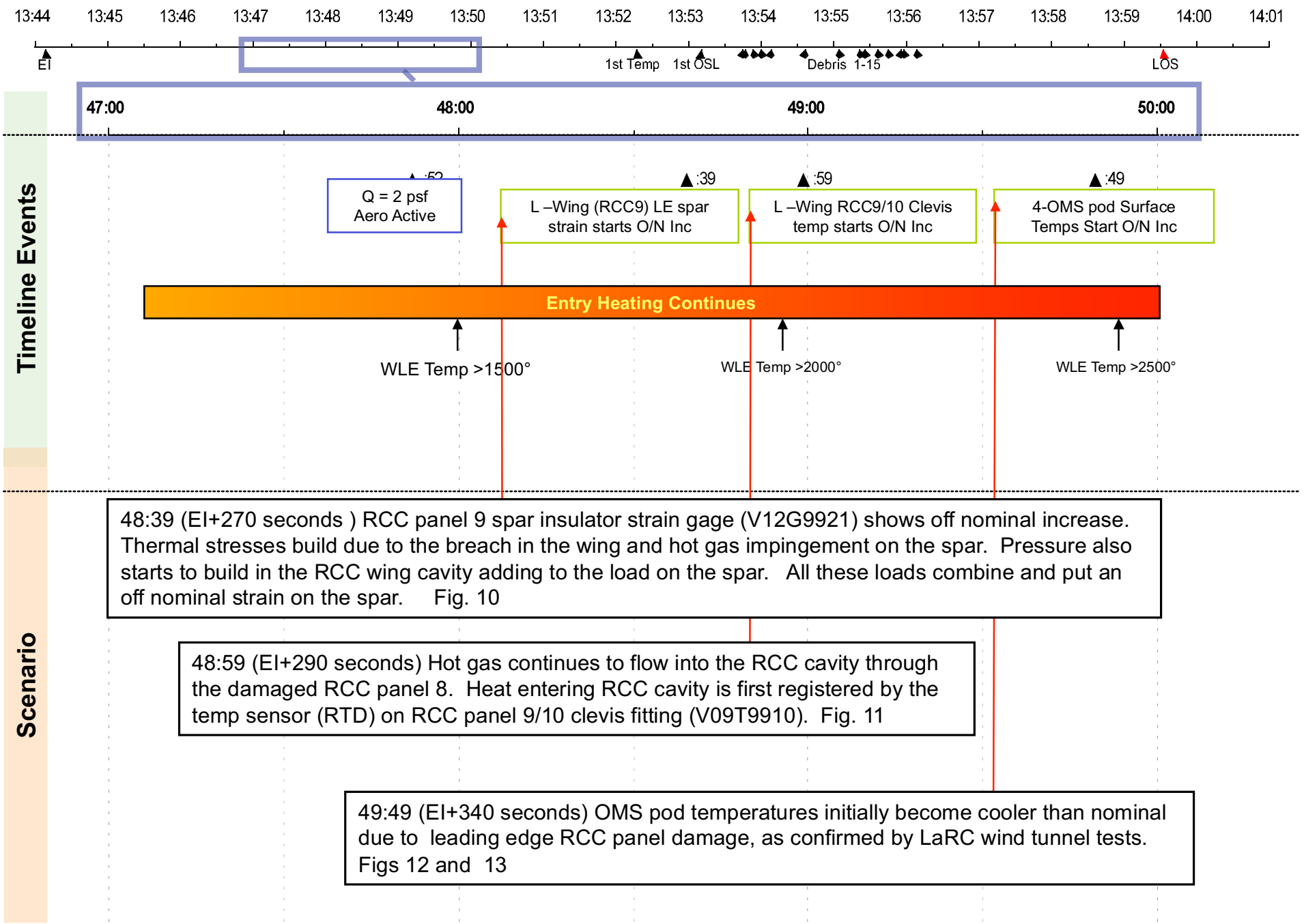


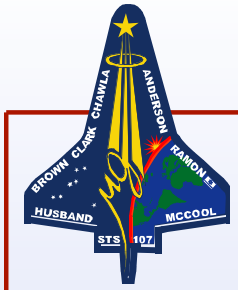
Missing panel #5



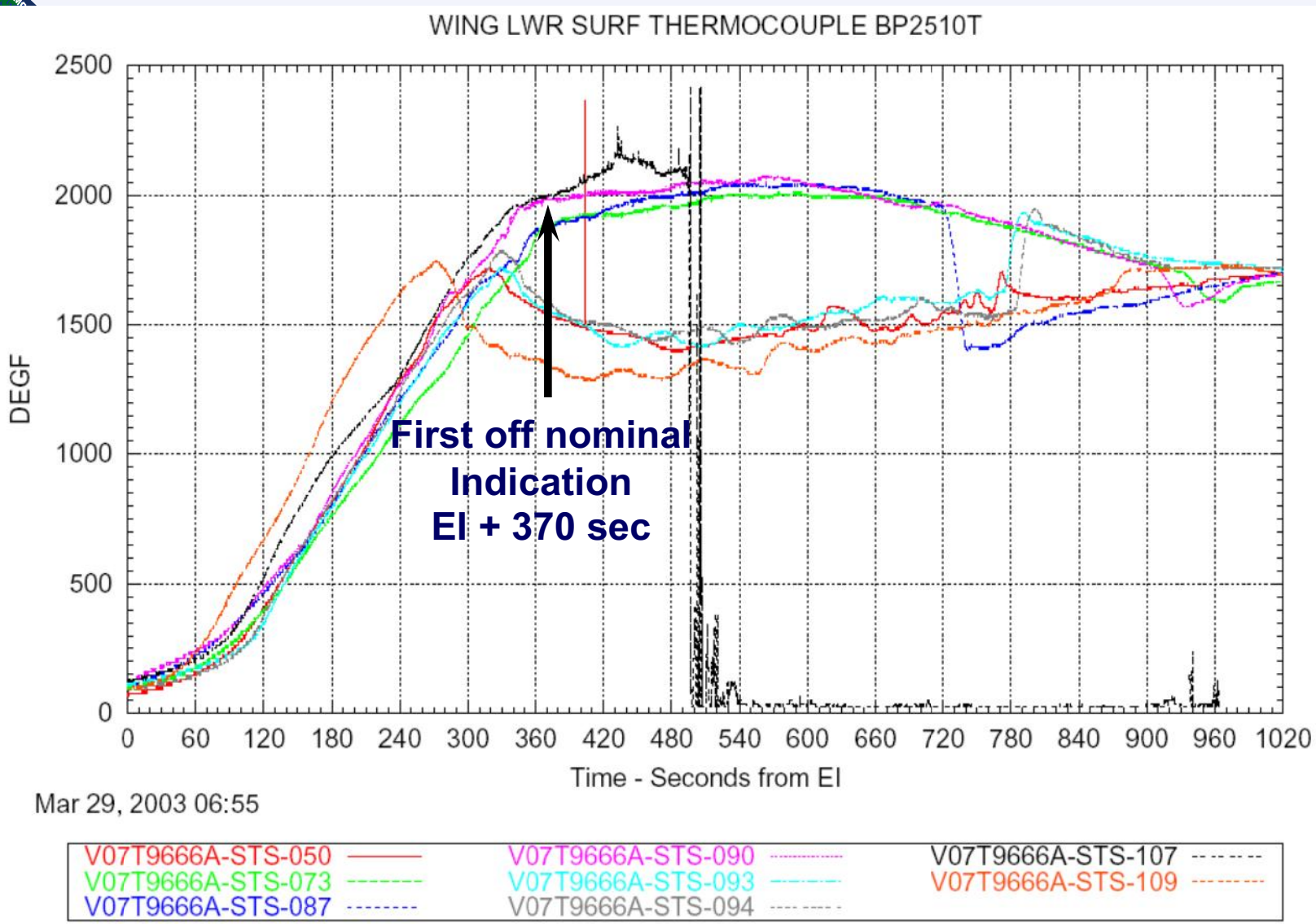
Missing panel #10

Note cooling trend on left OMS pod


13:44
13:45
13:46
13:47
13:48
13:49
13:50
13:51
13:52
13:53
13:54
13:55
13:56
13:57
13:58
13:59
14:00
14:01
EI
1st Temp
1st OSL
Debris
1-15
LOS
47:00
48:00
49:00
50:00
Timeline Events
Q = 2 psf
Aero Active
:39
L –Wing (RCC9) LE spar
strain starts O/N Inc
:59
L –Wing RCC9/10 Clevis
temp starts O/N Inc
:49
4-OMS pod Surface
Temps Start O/N Inc
Entry Heating Continues
WLE Temp >1500°
WLE Temp >2000°
WLE Temp >2500°
Scenario
48:39 (EI+270 seconds) RCC panel 9 spar insulator strain gage (V12G9921) shows off nominal increase. Thermal stresses build due to the breach in the wing and hot gas impingement on the spar. Pressure also starts to build in the RCC wing cavity adding to the load on the spar. All these loads combine and put an off nominal strain on the spar. Fig. 10
48:59 (EI+290 seconds) Hot gas continues to flow into the RCC cavity through the damaged RCC panel 8. Heat entering RCC cavity is first registered by the temp sensor (RTD) on RCC panel 9/10 clevis fitting (V09T9910). Fig. 11
49:49 (EI+340 seconds) OMS pod temperatures initially become cooler than nominal due to leading edge RCC panel damage, as confirmed by LaRC wind tunnel tests. Figs 12 and 13



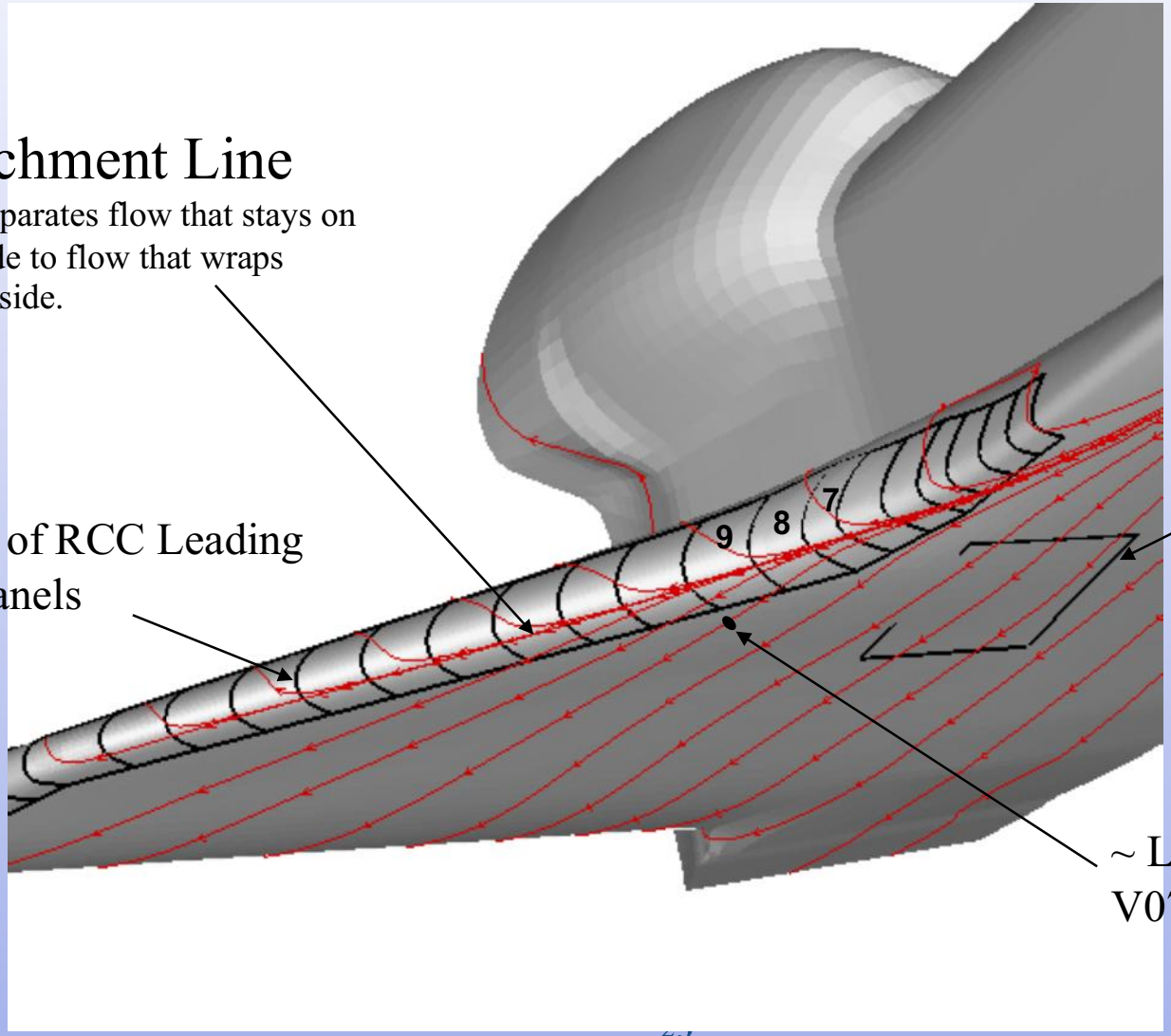
More OEX data and interpretation


WING LWR SURF THERMOCOUPLE BP2510T
DEGF
2500
2000
1500
1000
500
0
0 60 120 180 240 300 360 420 480 540 600 660 720 780 840 900 960 1020
Time - Seconds from EI
First off nominal
Indication
EI + 370 sec
Mar 29, 2003 06:55
V07T9666A-STS-050
V07T9666A-STS-073
V07T9666A-STS-087
V07T9666A-STS-090
V07T9666A-STS-093
V07T9666A-STS-094
V07T9666A-STS-107
V07T9666A-STS-109

NASA Langley/(Gnoffo) 0rbiter Surface Streamlines
EI+404; Mach=24.9; Alt.=243k ft

Attachment Line

- Line that separates flow that stays on windward side to flow that wraps around to leeside.

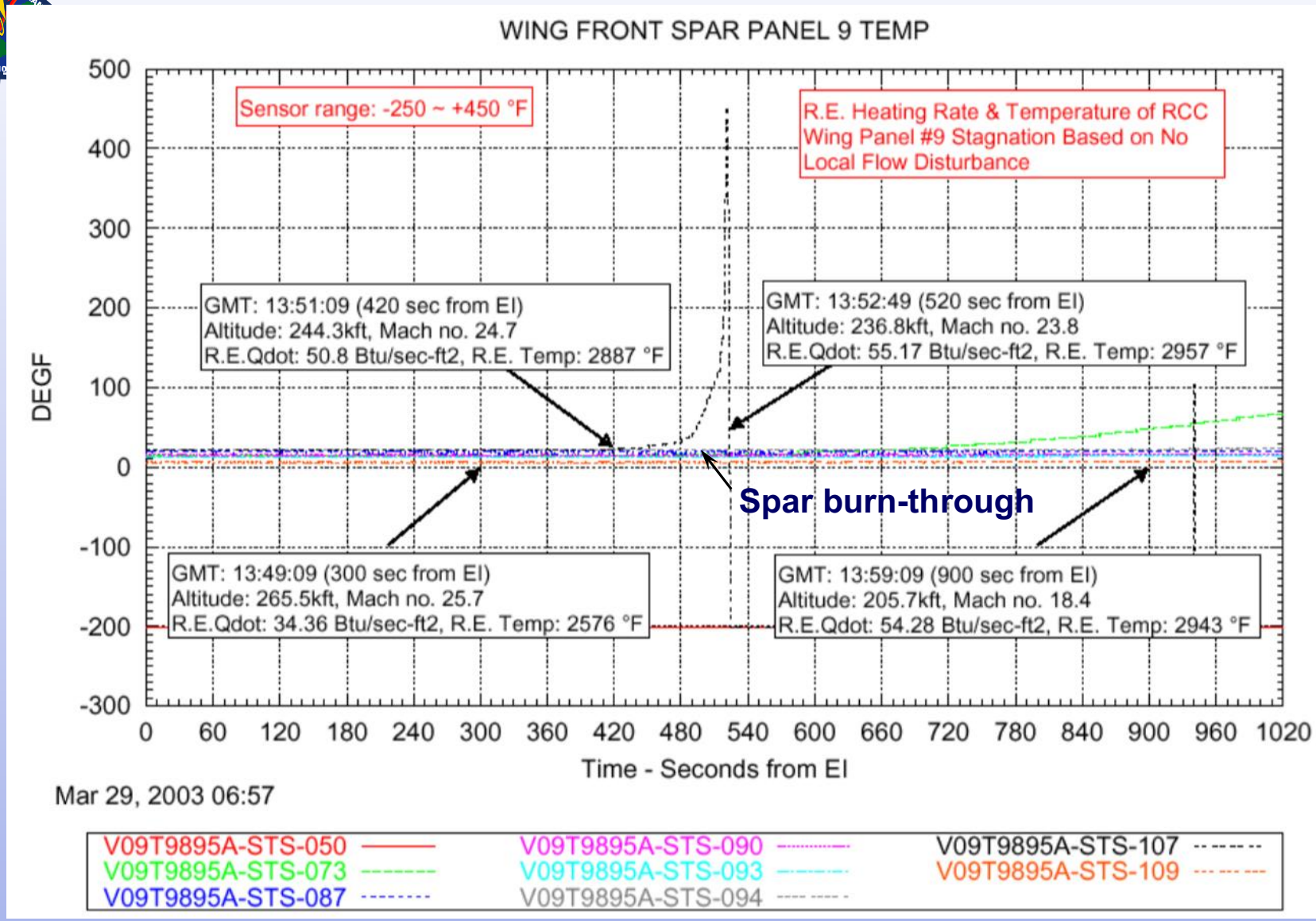


Outline of RCC Leading Edge Panels

Outline of Main Landing Gear Door

~ Location of V07T9666A

OEX/MADS STS-107 Flight Data



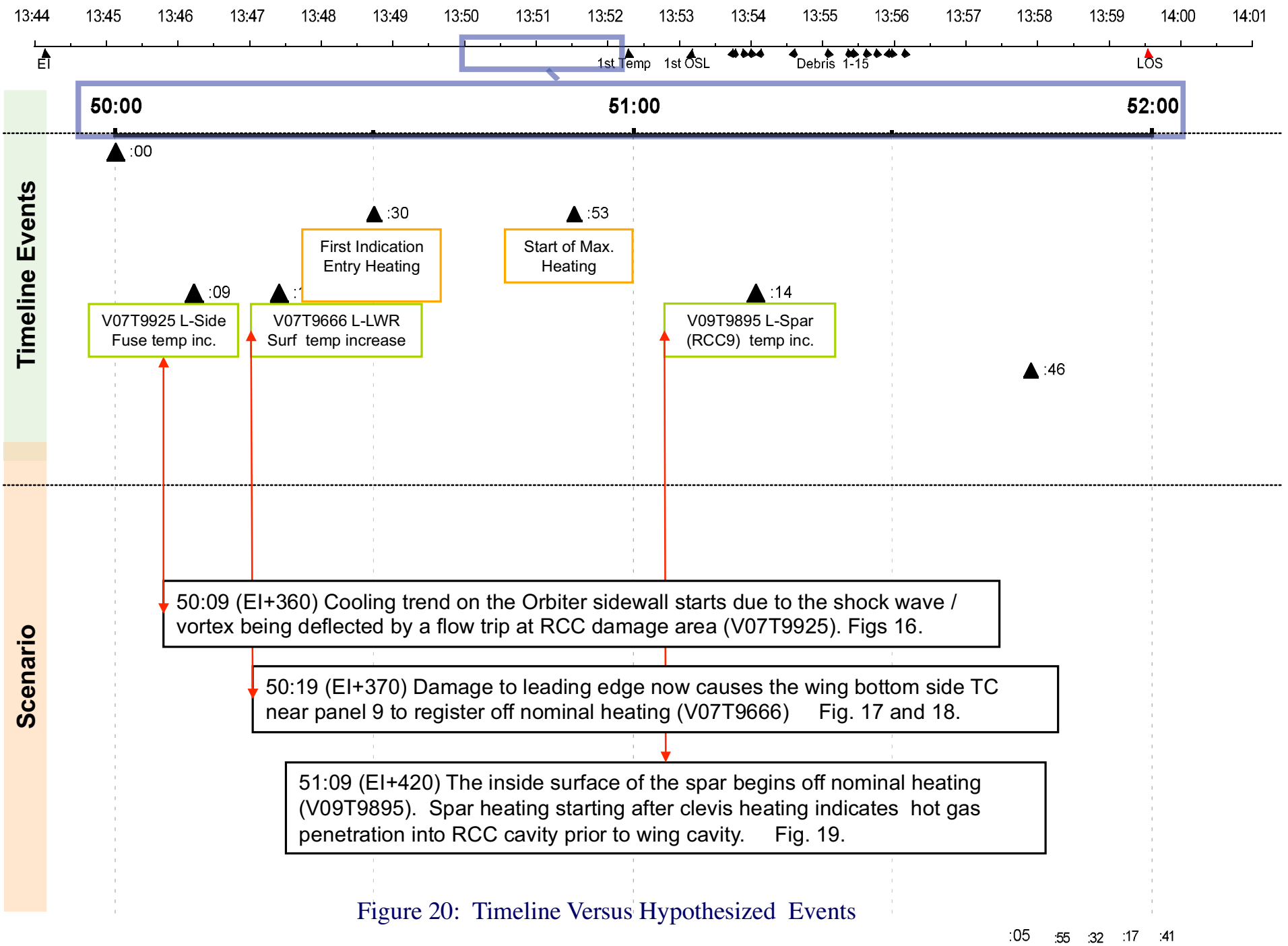
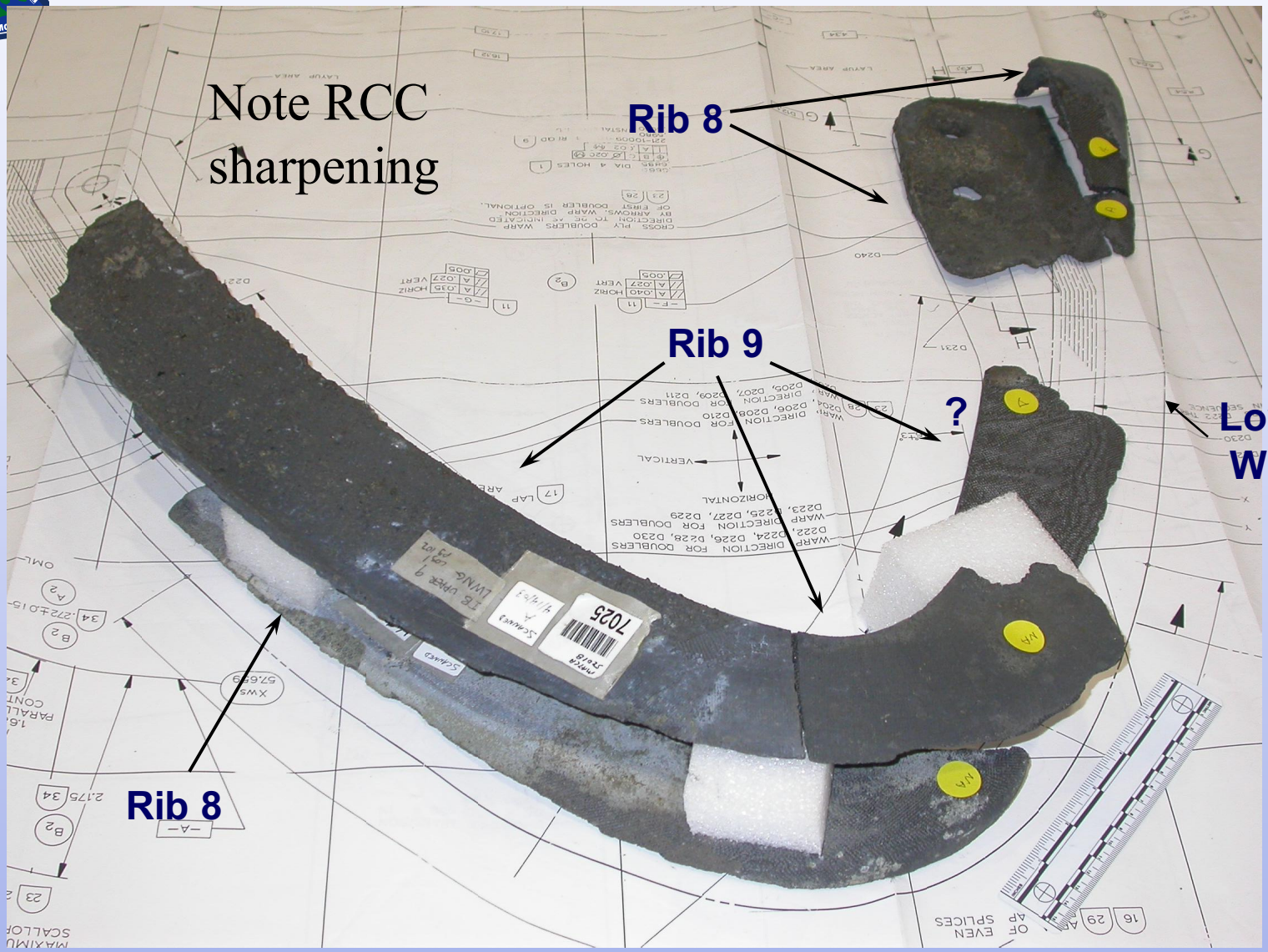


Figure 20: Timeline Versus Hypothesized Events

Analysis of the Columbia Debris

- Huge effort start & ongoing to recover debris from the field
- Huge effort at KSC to identify parts
- CAIB, NASA and Contractor teams conducting forensics at KSC

FRCC Panels 8/90 Ribs (Inboard View)



Reconstructed RCC Panel 8/9 Area

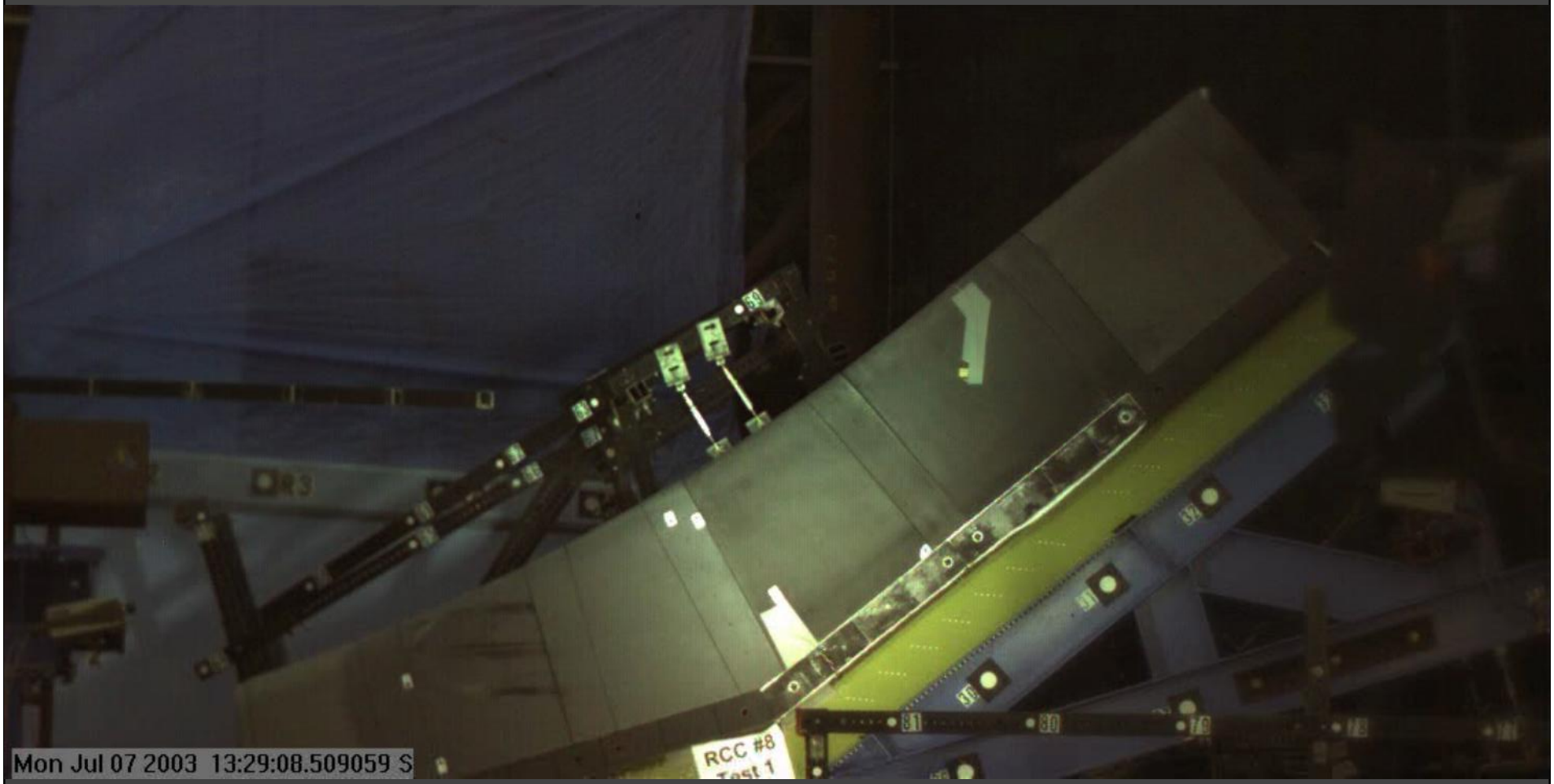
Probable Initial Breach in Panel 8

Close up of lower edge of panel 8/9

Foam Impact Testing

- CAIB lead: G. Scott Hubbard. Paul Wilde (CAIB) was lead on “Follow the Foam”. Large modeling effort led by JSC NASA and included work by Sandia
- Tests on tiles conducted first, little damage
- Then tests on fiberglass simulating RCC
- Tests on actual, aged RCC in one-for-one ground test
- Conclusive evidence that foam impact was initiating event

Wing Leading Edge Test Set Up


Mon Jul 07 2003 13:29:08.509059 S
RCC #8

Physical Cause

- Loss of Columbia and its crew was caused by breach in the Thermal Protection System on the leading edge of the left wing.
- The breach was initiated by a piece of insulating foam that separated from the left bipod ramp of the External Tank and struck the wing in the vicinity of the lower half of Reinforced Carbon-Carbon panel 8 at 81.9 seconds after launch.
- During re-entry, this breach in the Thermal Protection System allowed superheated air to penetrate the leading-edge insulation and progressively melt the aluminum structure of the left wing
- Weakening of the structure increased until aerodynamic forces caused loss of control, failure of the wing, and breakup of the Orbiter.

Acknowledgements Regarding "Follow the TPS"

- Howard Goldstein - Retired NASA
- Don Rigali- Retired Sandia
- NASA & NASA Contractor Engineering Staff

- Larry Korb
- Mike Ehret
- Don Hendrix
- Lisa Chu-Theilbar
- James Reuther
- Greg Kovacs
- Mark Tanner
- Jay Grinstead

References:

• Follow the TPS (Arnold, Goldstein and Rigali)
CAIB Report, Vol IV, Appendix F2, August, 2003
• Aero/Aerothermal/Thermal/Structures Team Final Report
CAIB Report, Vol V, Appendix G13, August, 2003

"This cause of exploration and discovery is not an option we chose; it is a desire written in the human heart... We find the best among us, send them forth into unmapped darkness, and pray they will return. They go in peace for all mankind, and all mankind is in their debt."

President George W. Bush, February 4, 2003