Volume IV
Appendix F.3
MADS Sensor Data

This Appendix presents three different Boeing analyses: MADS Instrumentation Evaluation, STS-107X1040 Spar Cap Strain Gage Assessment and Induced Thermal Strain Scenario. These presentations were identified as preliminary information at the time they were presented to the CAIB. The documents are now available to the public.

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MADS Instrumentation Evaluation

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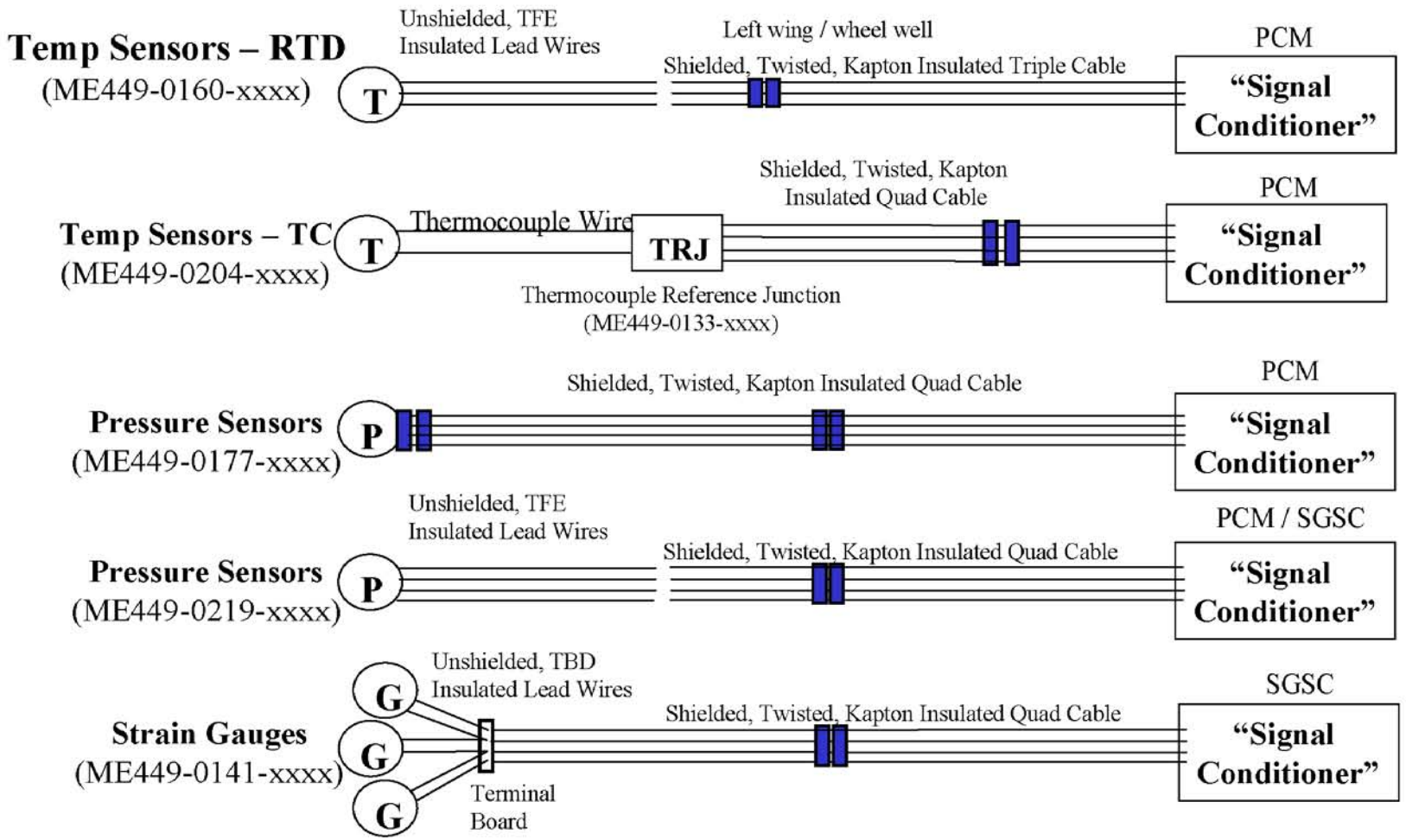
4/24/03

Instrumentation Subsystem Is Continuing to Assess the Reliability of the MADS Data

- Large Quantities of Measurements Develop Erratic Responses in the Vicinity of EI + 480 to 600 Seconds
  - Equivalent GMT is 1352 to 1354 GMT (EI: 1344:09 GMT)
- The Instrumentation Team Is Responsible for Determining Data Validity Based on Assessment of the MADS Avionics Telemetry Behavior
  - The goal is to establish a range or a point beyond which data validity is unreliable and convey that information to the MADS user community
- Where Possible, Failure Modes Were Developed to Explain the Invalid Data Observed
  - Sensor type segregation approach was utilized, that is
    - Pressures—Pulse Code Modulation (PCM) and Strain Gauge Signal Conditioner (SGSC)
    - Strains
    - Temperatures—Resistance Temperature Device (RTD) and Thermocouple
- General Statements Regarding the MADS System Performance Can Be Made Based on Assessments of the Telemetry

MADS Instrumentation Types



MADS Transducer and Avionics Failure Susceptibilities

- Excitation Voltage Commonality Within the MADS Avionics Can Provide for Perturbations in the MADS Data From Varying and Seemingly Unrelated Sensor Locations
  - For example, wiring anomalies in the left wing could result in erratic data from right wing sensors
- Specific Observations—SGSC Pressures
  - 24 left and right wing pressure measurements are biased in the PCM by Strain Gauge Signal Conditioners (SGSCs)
  - In the absence of the nominal excitation voltage, the PCM would detect the 500mV bias voltage (0 psi) which would be detectable in the MADS data
  - At ~1352:10 GMT, the voltage was 0 volts indicating that the excitation leads were shorted to signal minus
  - This would cause left and right wing pressure sensors to read 0 psi
  - The data from these sensors is invalid following ~1352:10 GMT

MADS Transducer and Avionics Failure Susceptibilities

- Specific Observations—Strain Gauges
  - Following installation, strain gauges are biased balanced in place to achieve 0 micro strains due to variations in the gauge and the effects of gauge installation
    - Biasing is achieved via potentiometer adjustment at the SGSC resulting in a non-zero voltage presented to the PCM
  - Typical signature observed in erratic strain data was characterized by off-scale excursions followed by a near zero response
  - Analysis of the data indicates that upper and lower range excursions are due to alterations in the resistance presented to the sensing bridge circuit
  - The subsequent non-zero response is believed to be the result of the bias voltage being reflected following gauge lead burn through
  - Strain gauge responses are to be considered invalid following the initial upper or lower range excursions

MADS Transducer and Avionics Failure Susceptibilities

- Specific Observations—Pressures
  - The pressure transducers use five volt excitation from the PCMs
    - Two transducer types are used—Kulite (ME449-0219-xxxx) and Statham (ME449-0177-xxxx)
  - Complete loss of the five volt excitation from the MADS PCM will cause the measurement to fail off scale low
  - Various shorting combinations could cause the sensors to read either off-scale high or off-scale low
  - Insulation degradation also provides for intermittent conductor-to-conductor shorts which could explain the upper to lower range excursions
  - Ultimately, the vast majority of pressures fail off-scale low which is attributed to sensor leads burned through and shorted and / or open circuited
  - Pressure measurements are considered invalid following excursions to upper or lower ranges

MADS Transducer and Avionics Failure Susceptibilities

- Specific Observations—Temperatures RTDs
  - The Resistance Temperature Device (RTD) is used to complete a wheatstone bridge internal to the MADS PCM
  - The bridge output is determined by the resistance between different leads on the RTD
  - Various shorting combinations could cause the sensors to read either off-scale high or off-scale low
  - Insulation degradation also provides for intermittent conductor-to-conductor shorts which would cause increases or decreases in the measurement value
  - RTD measurements are considered invalid following excursions to upper or lower ranges

MADS Transducer and Avionics Failure Susceptibilities

- Specific Observations—Temperatures Thermocouples
  - Thermocouple measurements use compensating reference junctions which are powered by 5 volt excitation from the PCMs
  - Loss of the 5 volt excitation will cause the measurement to fail off scale low
  - Various shorting combinations could cause the sensors to read either off-scale high or off-scale low
  - Insulation degradation also provides for intermittent conductor-to-conductor shorts which would cause increases or decreases in the measurement value
  - The majority of thermocouple temperatures fail off-scale low which is attributed to sensor leads burned through and shorted and / or open circuited
  - Thermocouple measurements are considered invalid following excursions to upper or lower ranges
  - Temperatures preceding the inflection point toward off-scale high are considered valid up to the point of rapid slope change

MADS Transducer and Avionics Failure Susceptibilities

- Specific Observations—Specific Temperature Set
  - A specific set of temperature measurements observed to display anomalous behavior during the STS-107 entry is similar to a previous unexplained anomaly on MADS PCM 1
  - Measurements V07T9636A, V07T9480A, V07T9489A, V07T9492A, V07T9522A which use MADS PCM 1 excitation output PPS089 all show a step in their signal level at approximately 13:52:20 GMT
  - Measurements V07T9253A, V07T9270A, V07T9468A, V07T9470A, V07T9478A which use MADS PCM 1 excitation output PPS087 showed a similar failure signature during STS-73, STS-75 and STS-78 on MADS PCM s/n 304
  - After STS-78, the PCM unit was removed from the vehicle and shipped to the vendor, B.F. Goodrich, for TT&E and test
    - The unit was tested at ambient, hot and cold temperatures without repetition of the failure condition
  - The failures repeated on STS-80, STS-94 and STS-87.
  - The cause and mechanism of this failure signature is unknown, however it is independent of the MADS PCM

STS-107 MADS Temperature Data
RCC Panel 9 Ascent Data

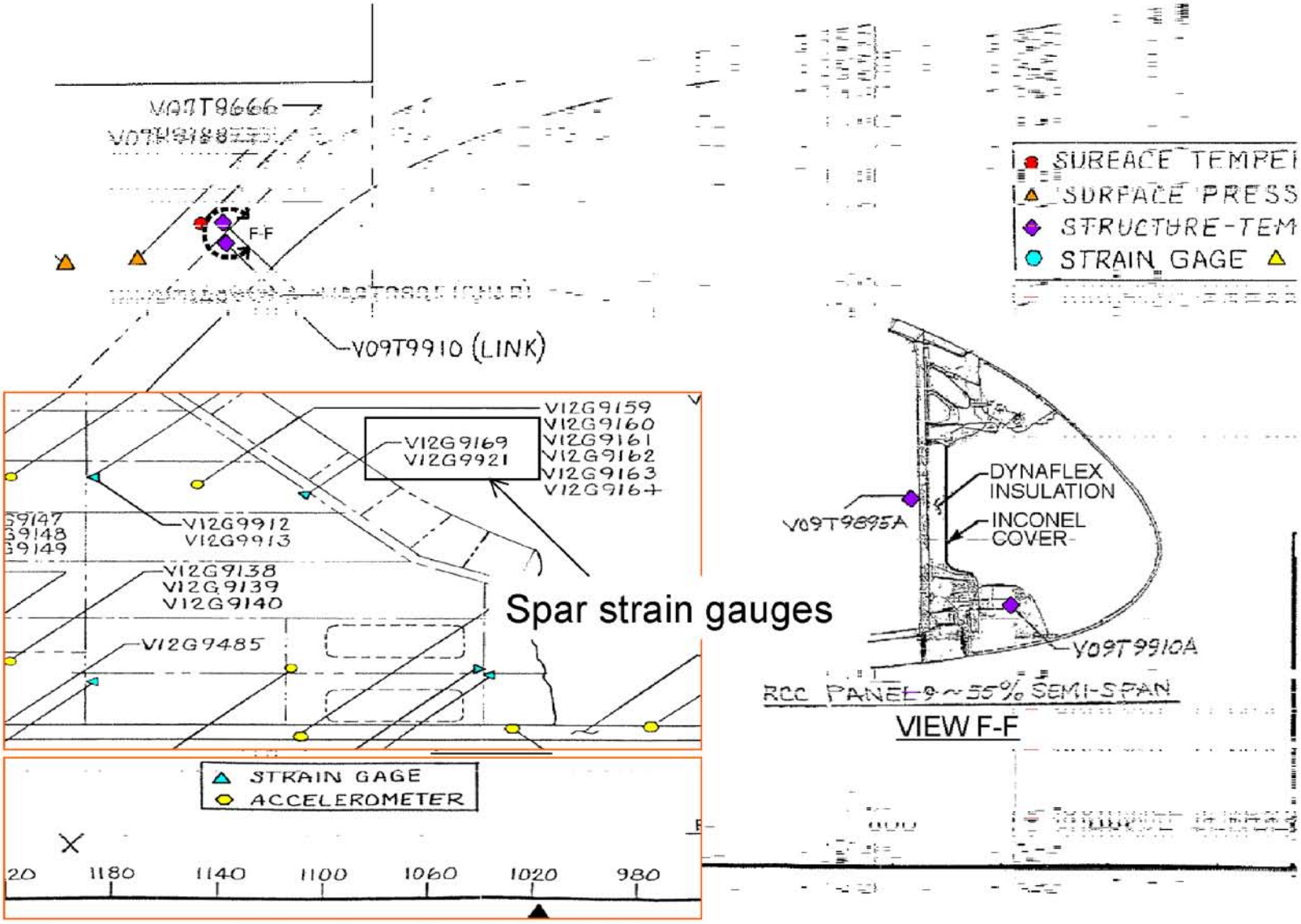
Ascent Response on RCC Panel 9 Spar

- Compared STS-107 Data Against Previous OV-102 Mission Data: 50, 73, 94, 87, 90, 93, and 109
  - Mission: launch date, GMT time, inclination, beta angle
  - STS-107: 01/16/03, 15:38: 59, 39°, -55.7°
  - STS-109: 03/01/02, 11:22:01, 28.45°, -7.0°
    - Flight preceding STS-107
  - STS-93: 07/23/99, 04:30:59, 28.45°, +47.8°
  - STS-90: 04/17/98, 18:18:59, 39°, -7.6°
  - STS-87: 11/19/97, 19:46:00, 28.45°, -38.4°
  - STS-94: 07/01/97, 18:02:00, 28.45, -4.7°
  - STS-73: 10/20/95, 13:53:00, 39°, -49.3°
  - STS-50: 06/25/92, 16:12:23, 28.5°, -4.4°

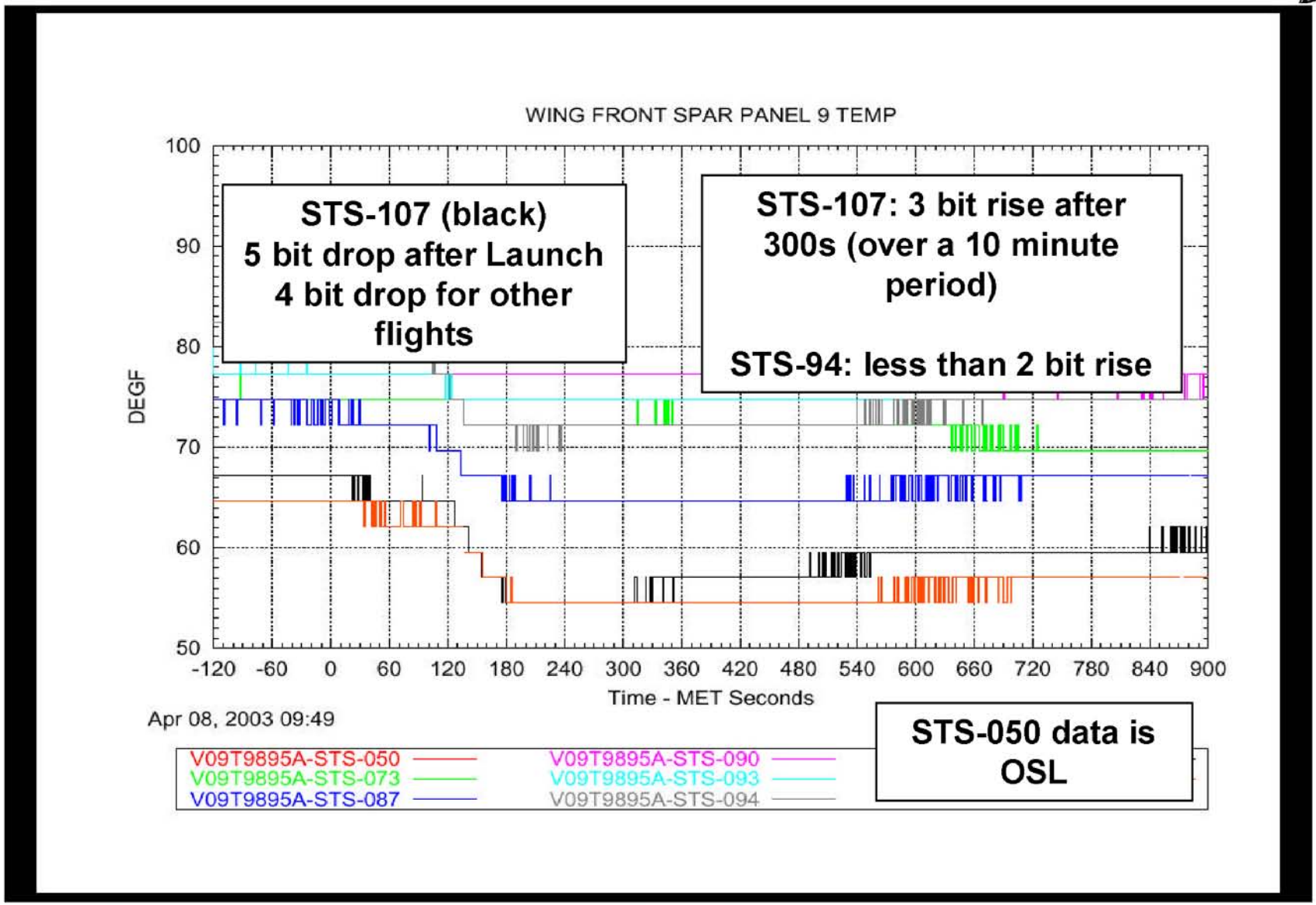
RCC Panel 9 Spar Temperature Data - Ascent

- Reviewed Previous OV-102 Ascent Data
  - STS-107 has earliest warming indication at 310 seconds
  - STS-107 has only occurrence of a 3 bit (7.5°F) warming during ascent, 67°F initial temp.
    - STS-94, a summer launch with 82°F initial temp, had less than a 2 bit rise
  - No spar temperature sensor on other vehicles

RCC Panel 9 Sensor Locations



RCC Panel 9 Spar Response - Ascent



RCC Panel 9 Spar Data Bit Summary

OV-102 Columbia	Ascent Bits Down/Up in 900 seconds RCC Panel 9 Spar Temp V09T9895a
STS-73 10/20/95	2/0
STS-75 02/22/96	3/0
STS-78 06/20/96	3/0
STS-80 11/19/96	1/0
STS-83 04/04/97	2/0
STS-94 07/01/97	5/2 (82 degF initial temp)
STS-87 11/19/97	4/1
STS-90 04/17/98	1/0
STS-93 07/22/99	1/0
STS-109 03/01/02	4/1
STS-107 01/16/03	5/3 (67 degF initial temp)

STS-107 MADS Temperature Data Entry

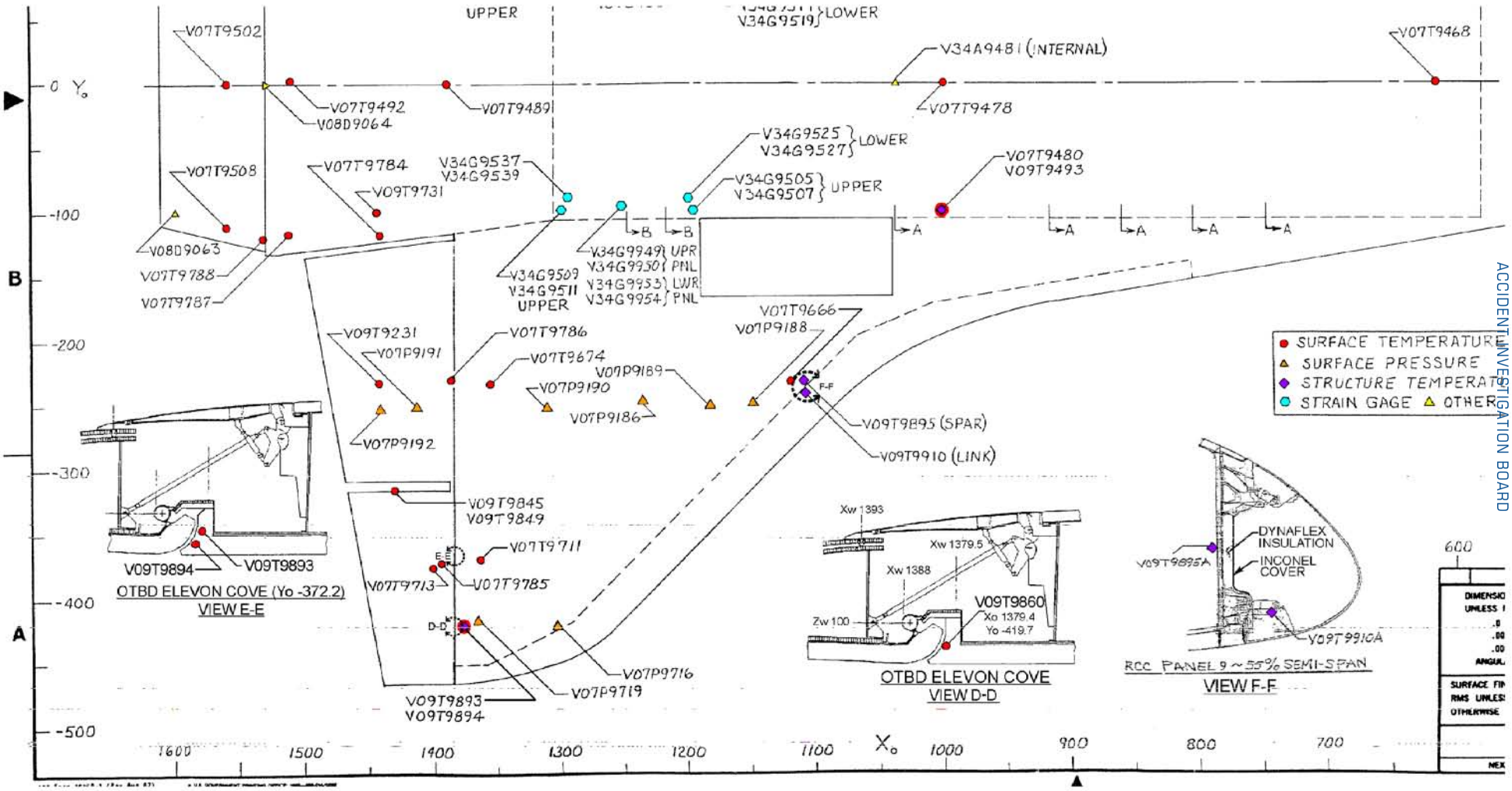
MADS Entry Data Review Process

- Compared STS-107 Data Against Previous OV-102 Mission Data: STS-50, 73, 94, 87, 90, 93, and 109
  - Mission: weight, inclination, transition from laminar to turbulent flow, altitude, center of gravity xo at EI
  - STS-107: ~233,995 lbs, 39°, Mach NA, 148 nm, 1078.27
  - STS-109: ~222,500 lbs, 28.45°, Mach ~8.7, 290 nm, 1083.8
    - Flight preceding STS-107
  - STS-93: ~203,300 lbs, 28.45°, Mach ~8.1, 148 nm, 1098.9
  - STS-90: ~233,500 lbs, 39°, Mach ~8.1, 142 nm, 1081.4
  - STS-87: ~233,400 lbs, 28.45°; Mach ~8.9, 153 nm, 1082.2
  - STS-94: ~231,750 lbs, 28.45°, Mach ~16.5, 164 nm ,1079.9
  - STS-73: ~231,300 lbs, 39°, Mach ~19.2, 142 nm, 1082.4
  - STS-50: ~227,000 lbs, 28.45°, Mach ~9.4, 146 nm, 1080.7

Temperature Observations

- Observations on 49 Temperature Measurements
  - All nominal response to MADS data loss EI+965 (14:00:14.490 GMT) – 2 sensors in RCC chin panel structure
  - All bad data – 2 sensors (pre-existing condition, door insulation and chin panel surface)
  - Trend to off-scale low at ~EI+490 seconds (13:52:24 GMT) – 15 sensors, all left wing
  - Sharp 300 to 350°F temp increase at ~EI+490 - 3 sensors,
    - LWR Xo 1004.1, Yo –99.8; Xo 1391.5, Yo 0.0; Xo 1511.1, Yo 1.3
  - Off-nominal trend (cooling) at ~EI+344 (13:49:53 GMT) seconds followed by off-nominal heating at ~EI+520 seconds until erratic temp trend at ~EI+933 seconds (13:59:42.49 GMT) – 14 sensors, left side and left pod
  - Off-nominal temperature increase start ~EI+290 sec - RCC Panel 9 spar and clevis

Lower Surface Temperatures and Pressures



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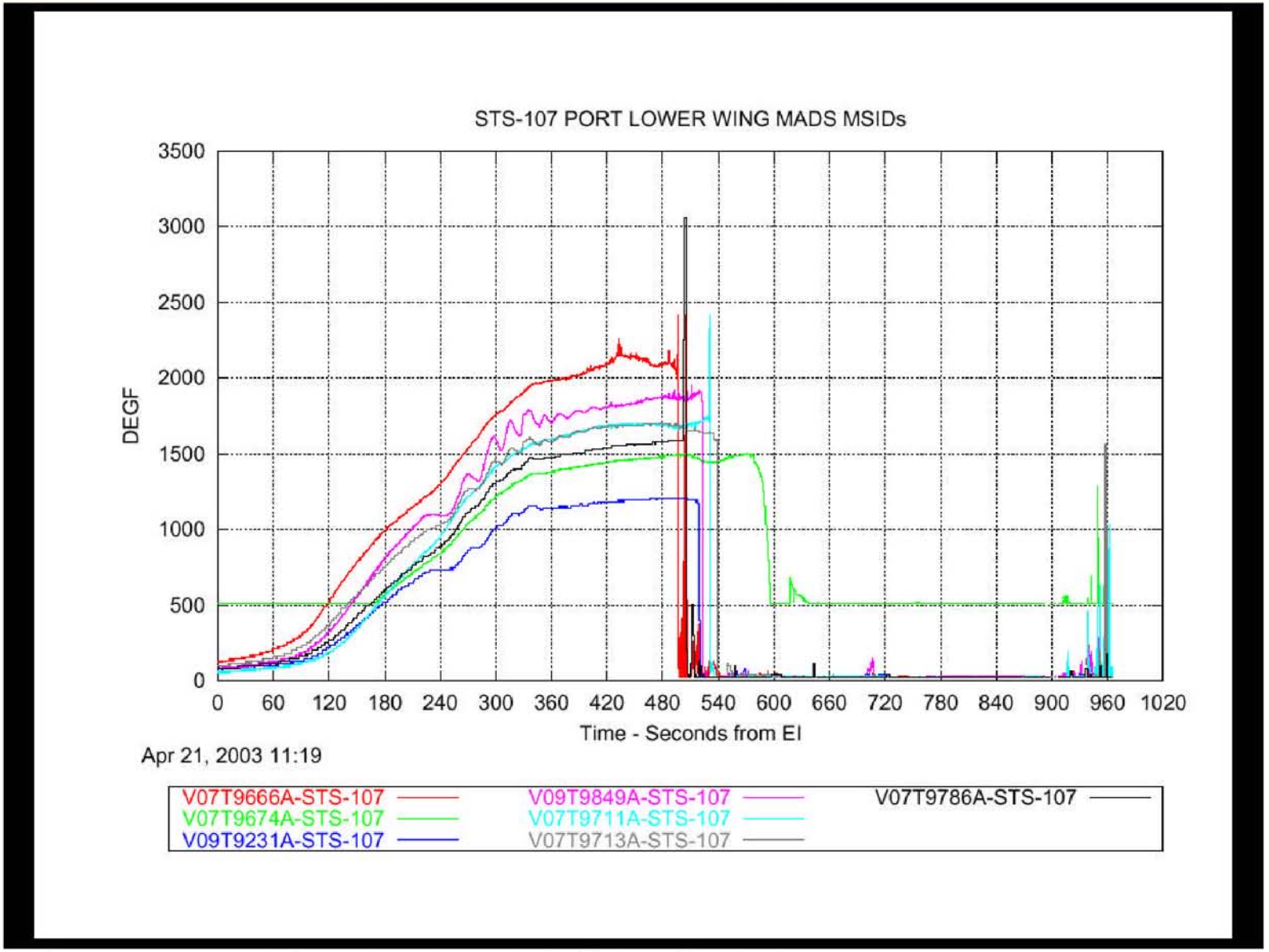
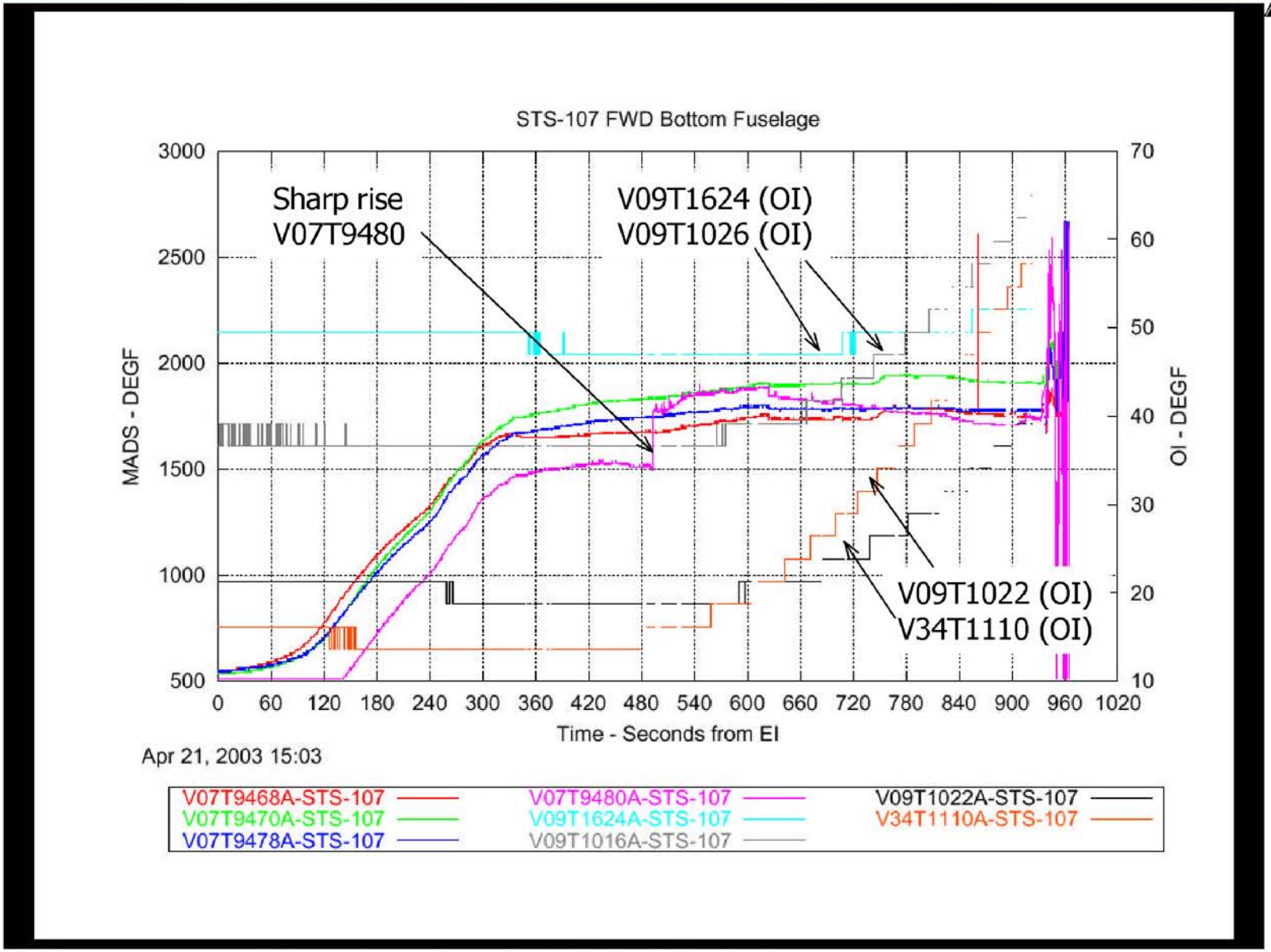
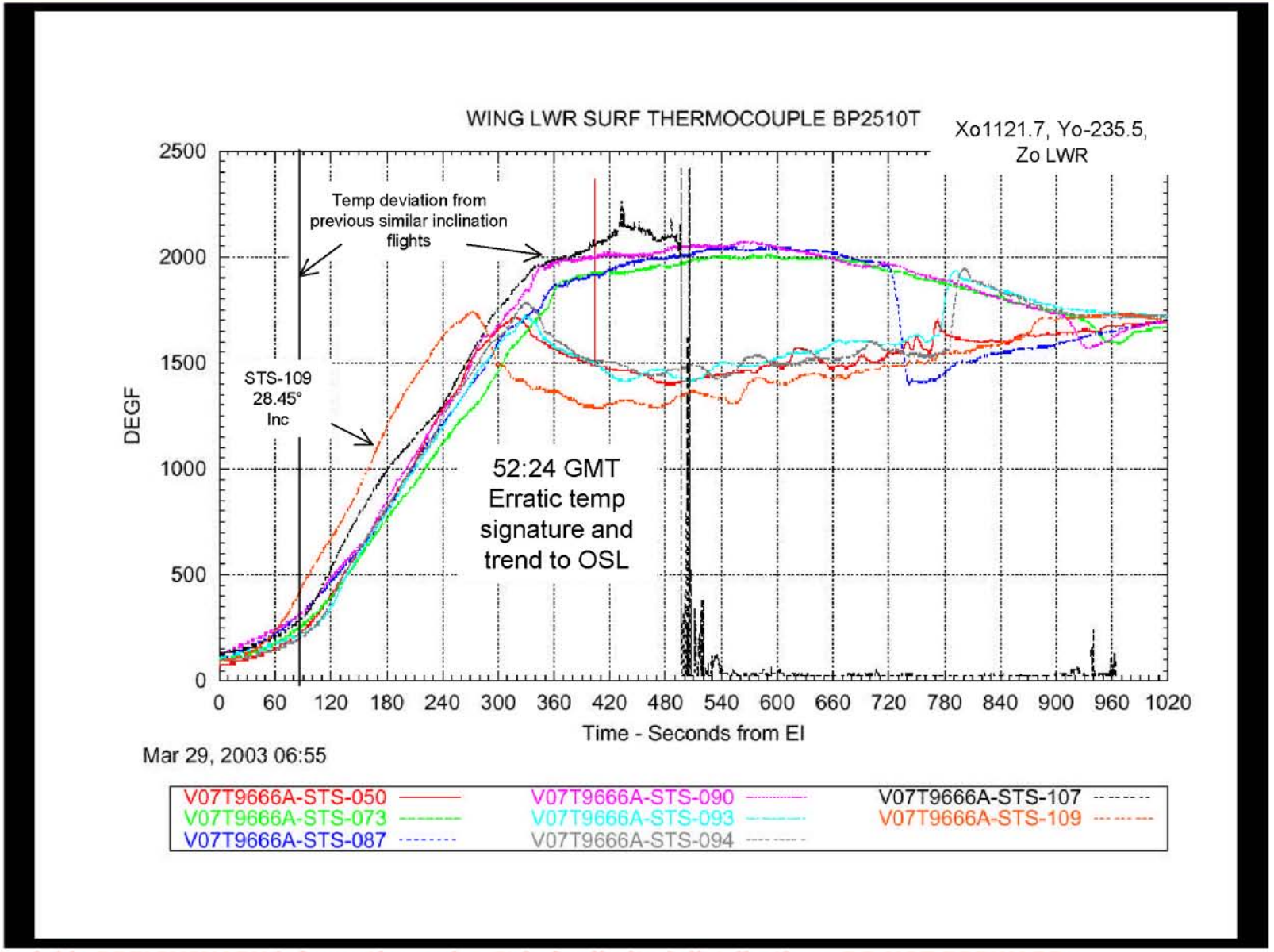
Lower Wing Surface Temperatures STS-107



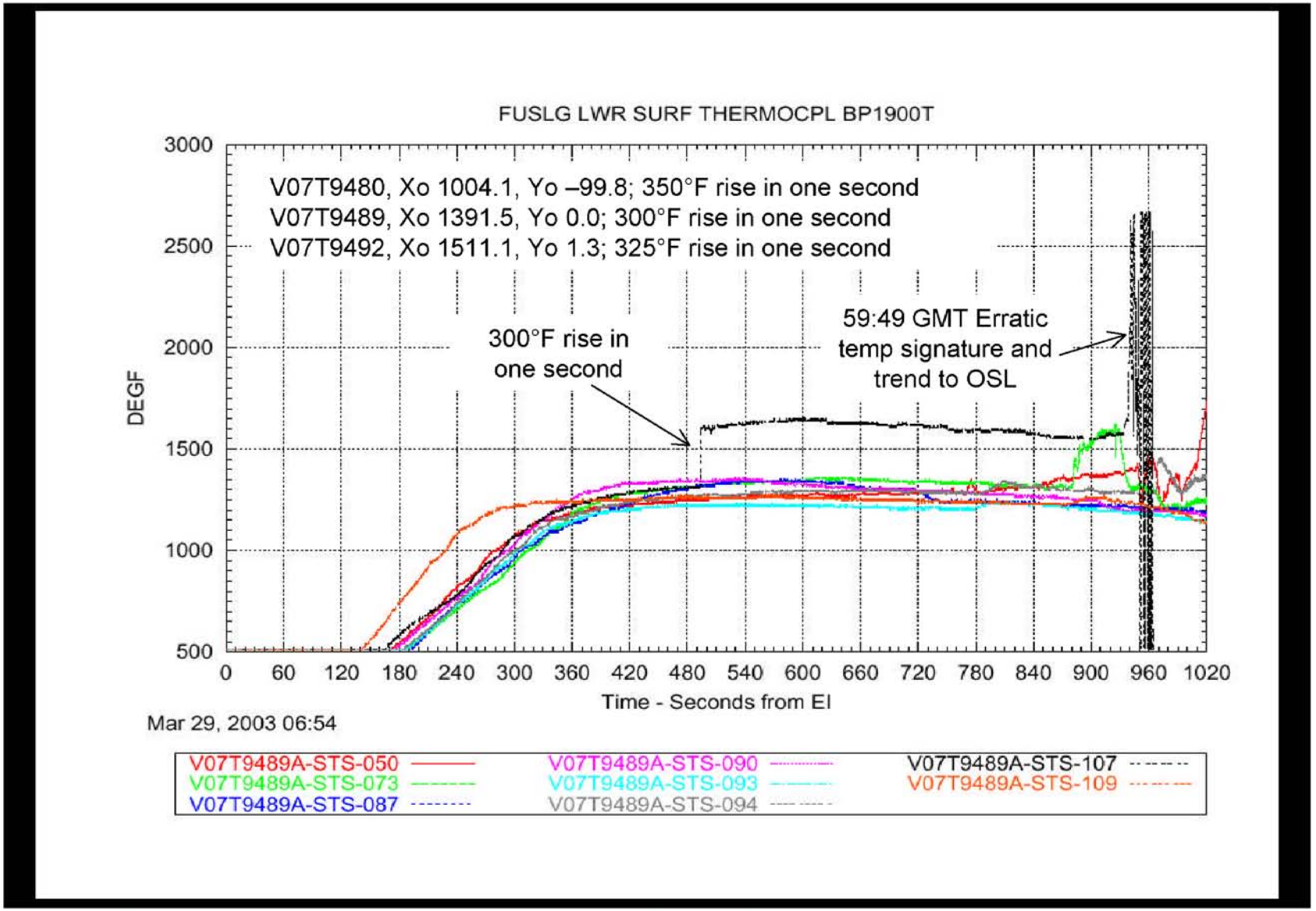
Lower Surface Sharp Temp Rise and Bondline OI



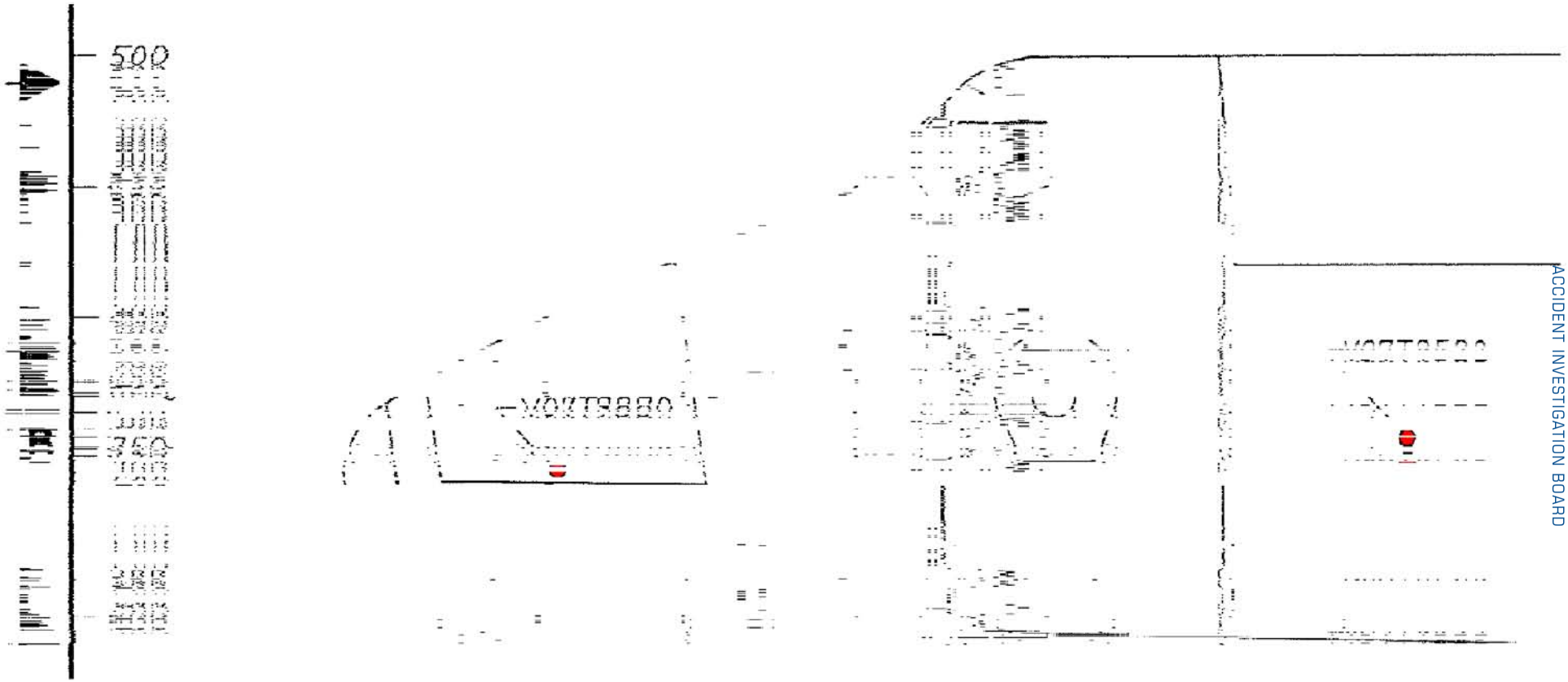
Trend to OSL & Early Warming Trend



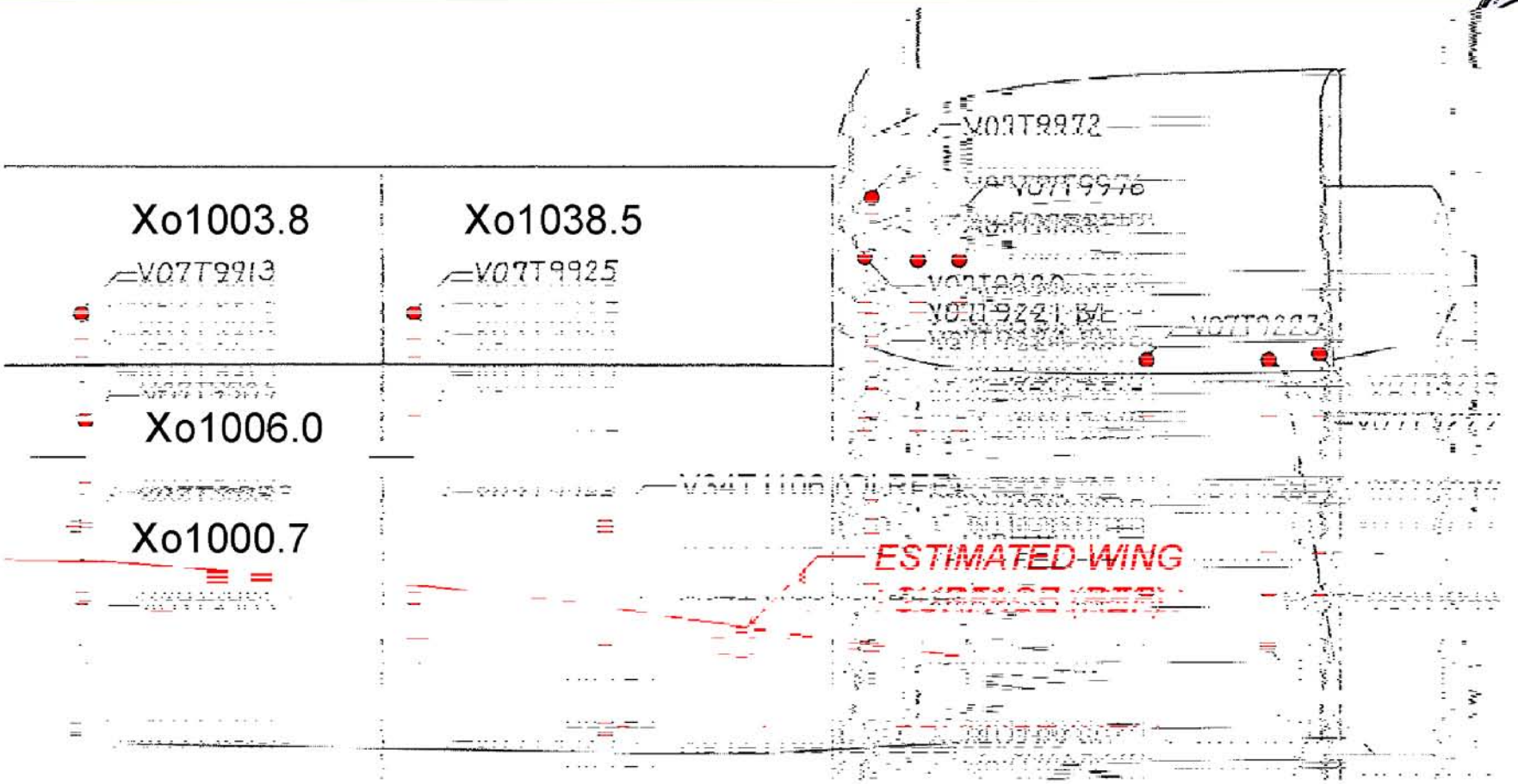
Sharp Temp Rise



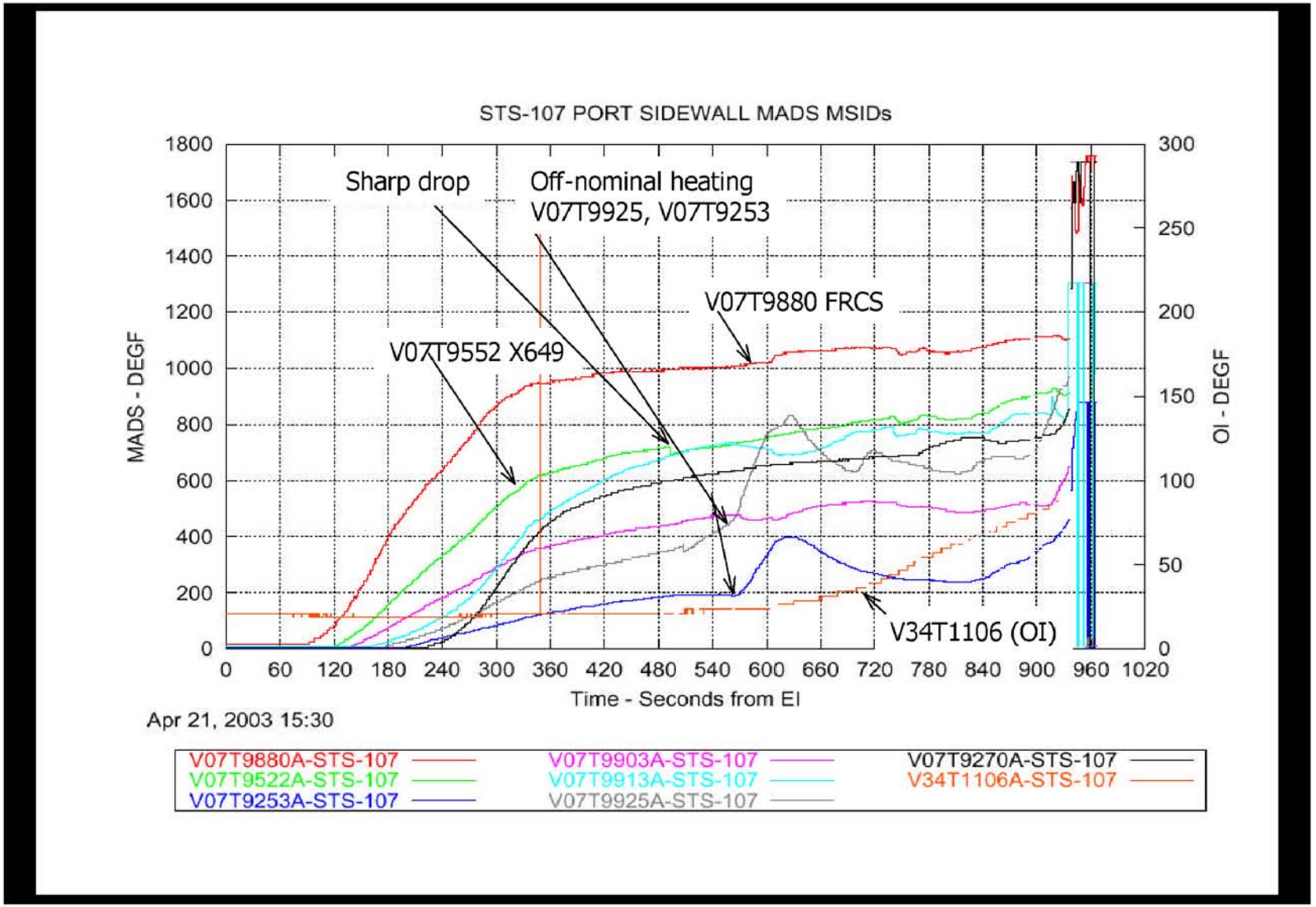
Left Side Temperature Sensor Locations



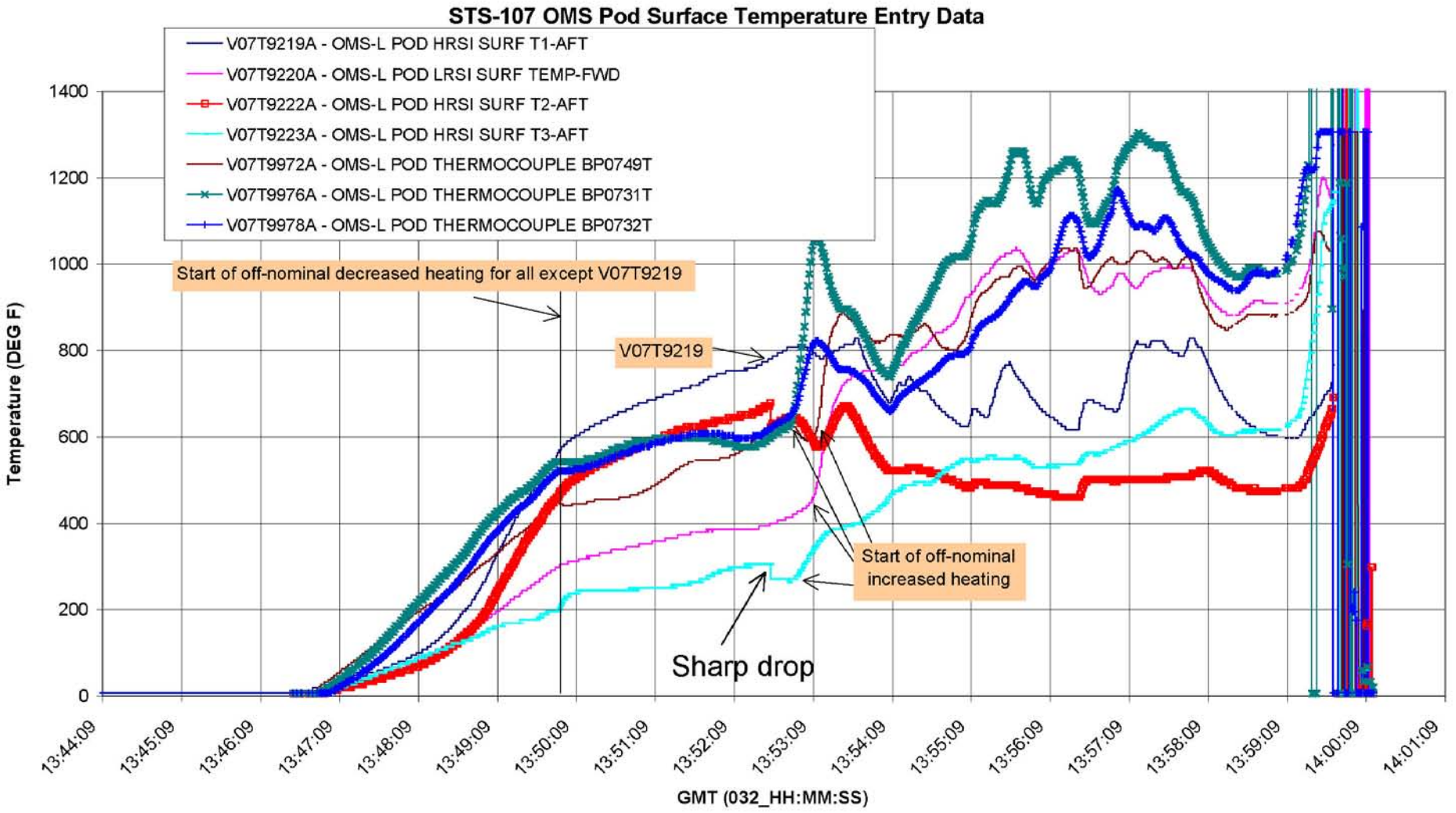
Left Side Surface Temperature Locations



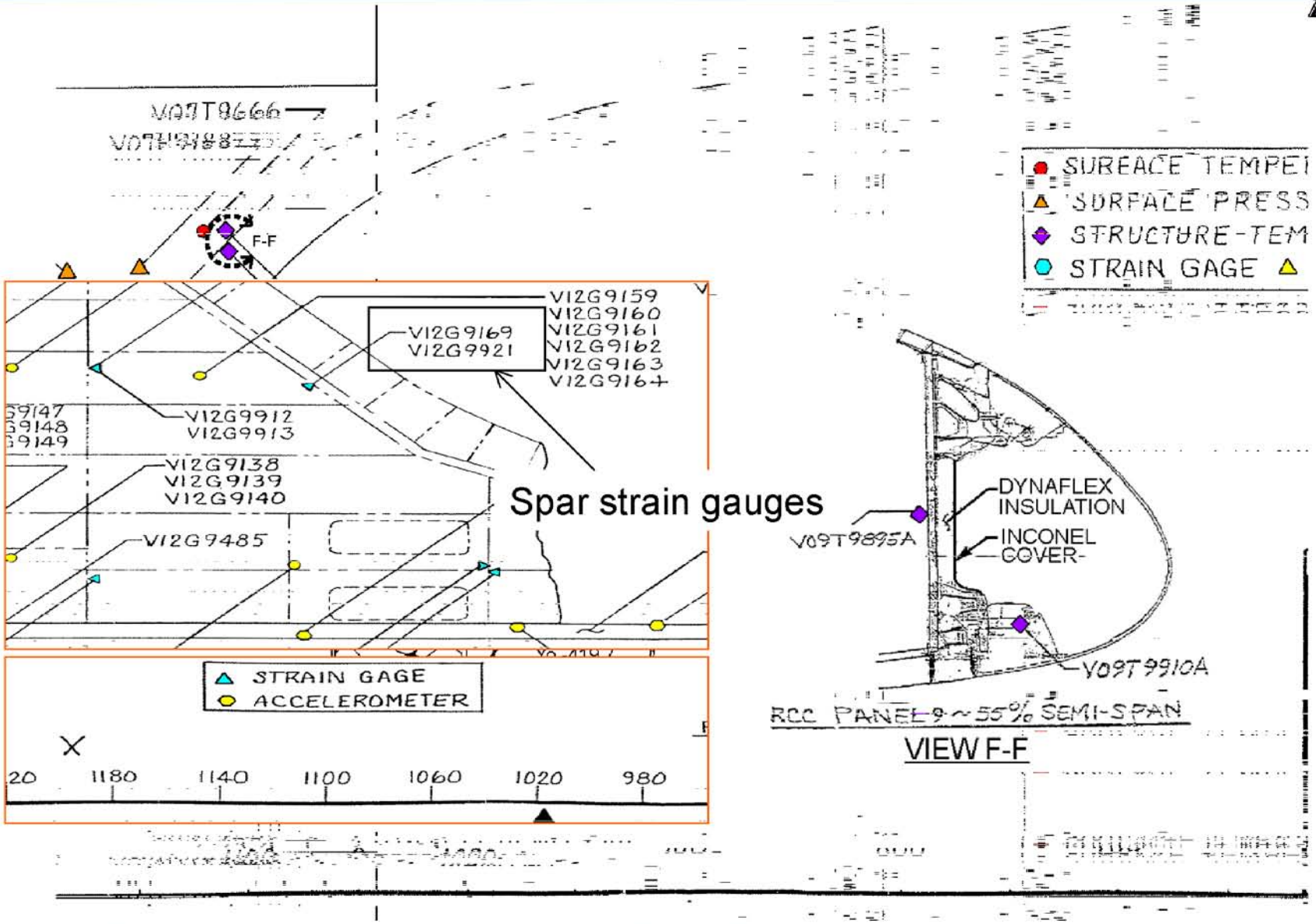
Left Side Surface and OI Temperatures



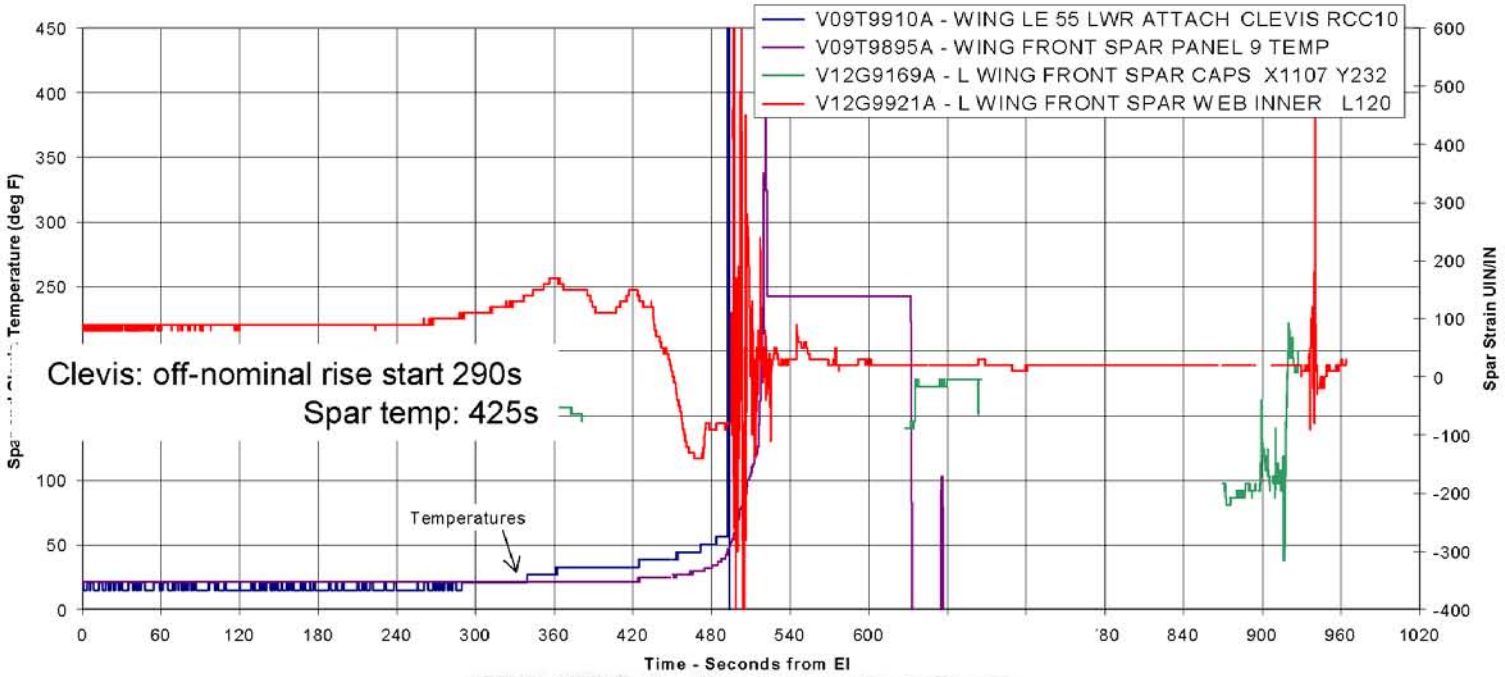
Left Pod Surface Temperatures - Entry



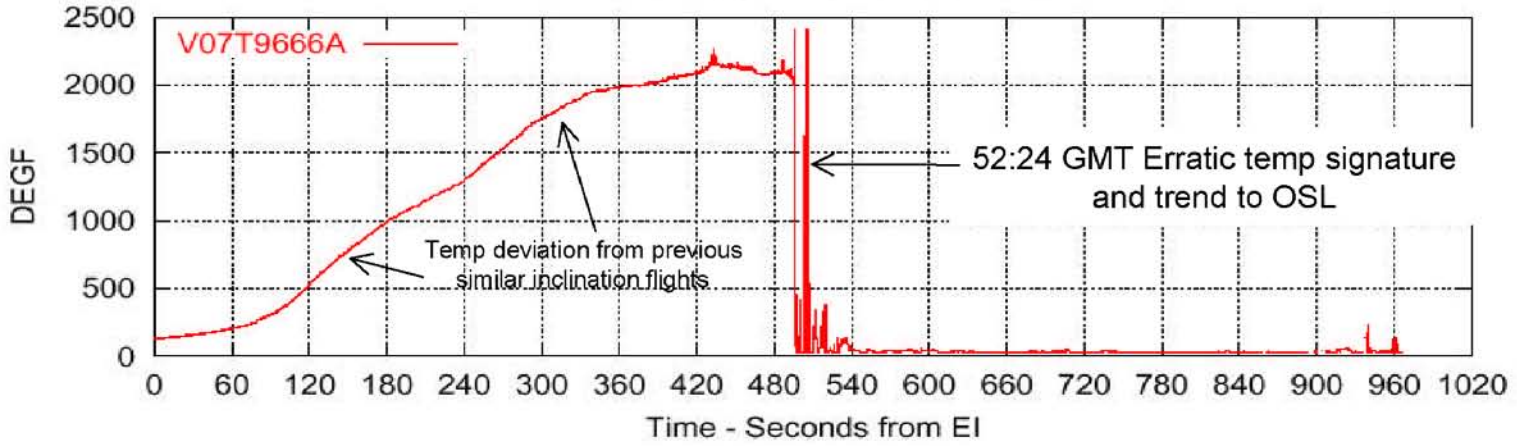
RCC Panel 9 Sensor Locations



RCC Panel 9 Area Temp & Strain



STS-107 Entry Temperature vs Strain



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STS-107 MADS Strain Gauge Data Entry

Summary

- A Number of MADS Strain Gauges Were Identified As Showing Abnormal Data Trends Versus Typical Strain Gauge Responses Observed on STS-107 entry
- Abnormal Gauges Were Grouped and Plotted Together According to Location on the Vehicle
- An Examination Was Performed for Strain and Temperature Gauges Near Left Wing RCC Panel #9
- Several Immediate Observations May Be Made from the Data
  - A number of other studies are currently in work

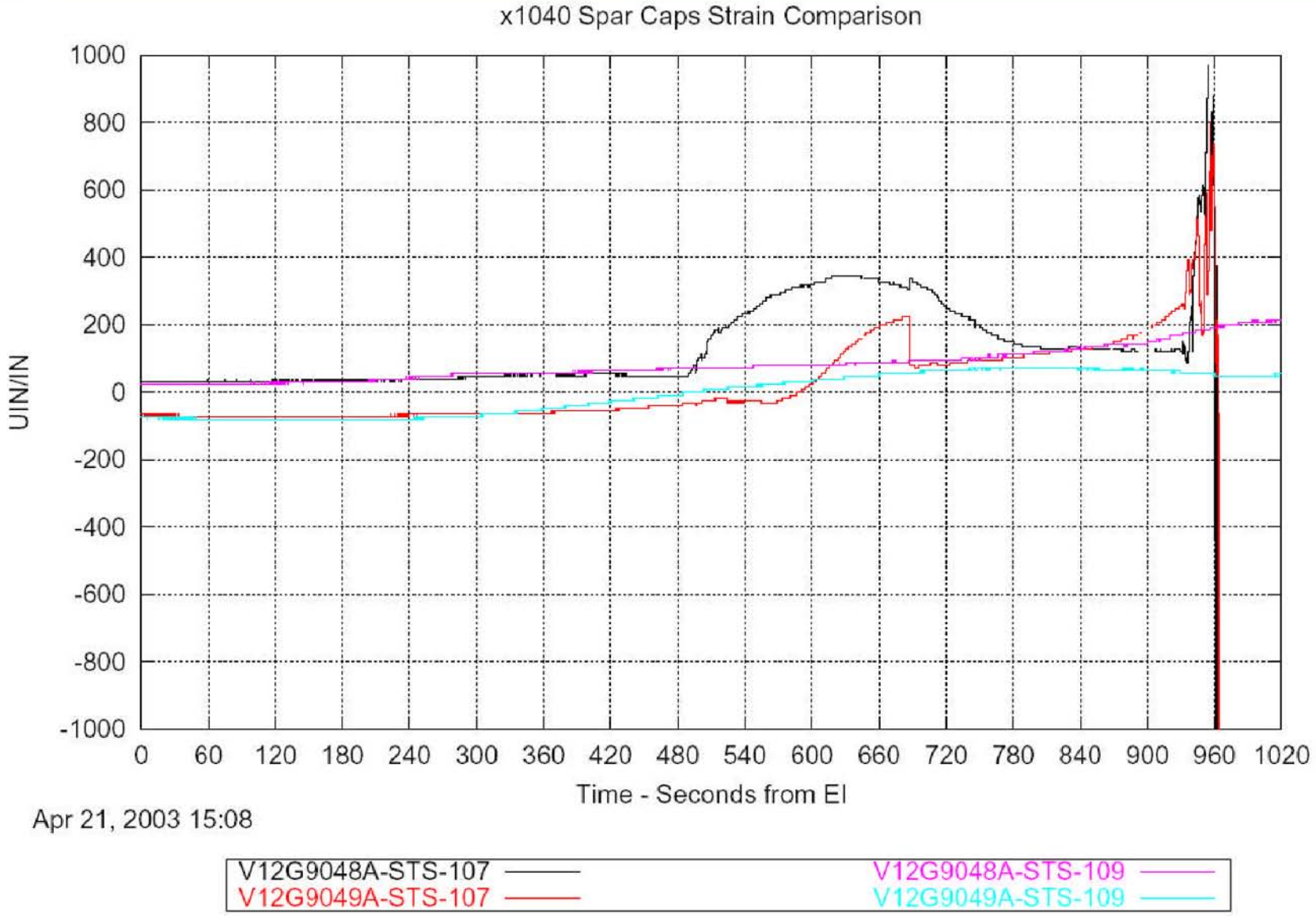
Abnormal Gauge Groupings

- Left Wing, x1040 Spar Gauges
- Mid Fuselage Gauges
- Right Wing Spar Cap Gauges
- Right Wing Skin Gauges @ x1334
- Right Wing Skin Gauges @ x1217.9
- Right Wing Skin Gauges @ x1276

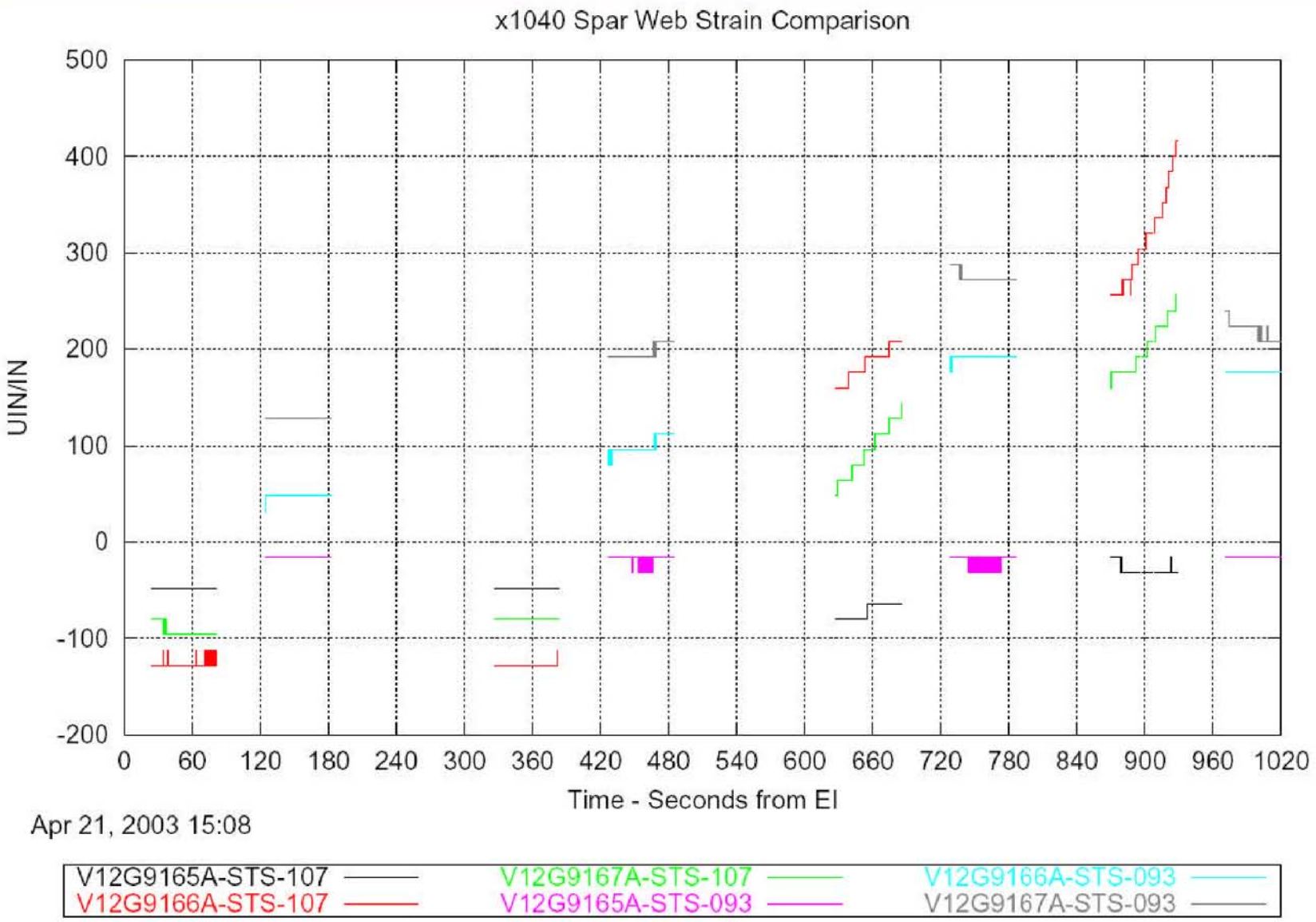
Data Observations/Future Work

- Left Wing x1040 Spar Cap Gauges Show an Anomalous Trend Initiating Between EI +500 and EI +600 Seconds. Web Gauges Have "Snapshot Mode" Data Which Suggest Off-nominal Trending After EI +500 Seconds
  - The spar cap gauges are two of only three left wing gauges which did not fail prior to vehicle breakup
  - Further analysis is in work to assess potential explanations for these anomalous signatures
- Some Mid Fuselage and Right Wing Spar Cap Gauges Show Mild Discrepancies Versus Previous Flights
  - Discrepancies are more subtle
- A Number of Right Wing Skin Gauges Show off Nominal Trending Initiating Near EI +500 Seconds
  - Currently under further investigation

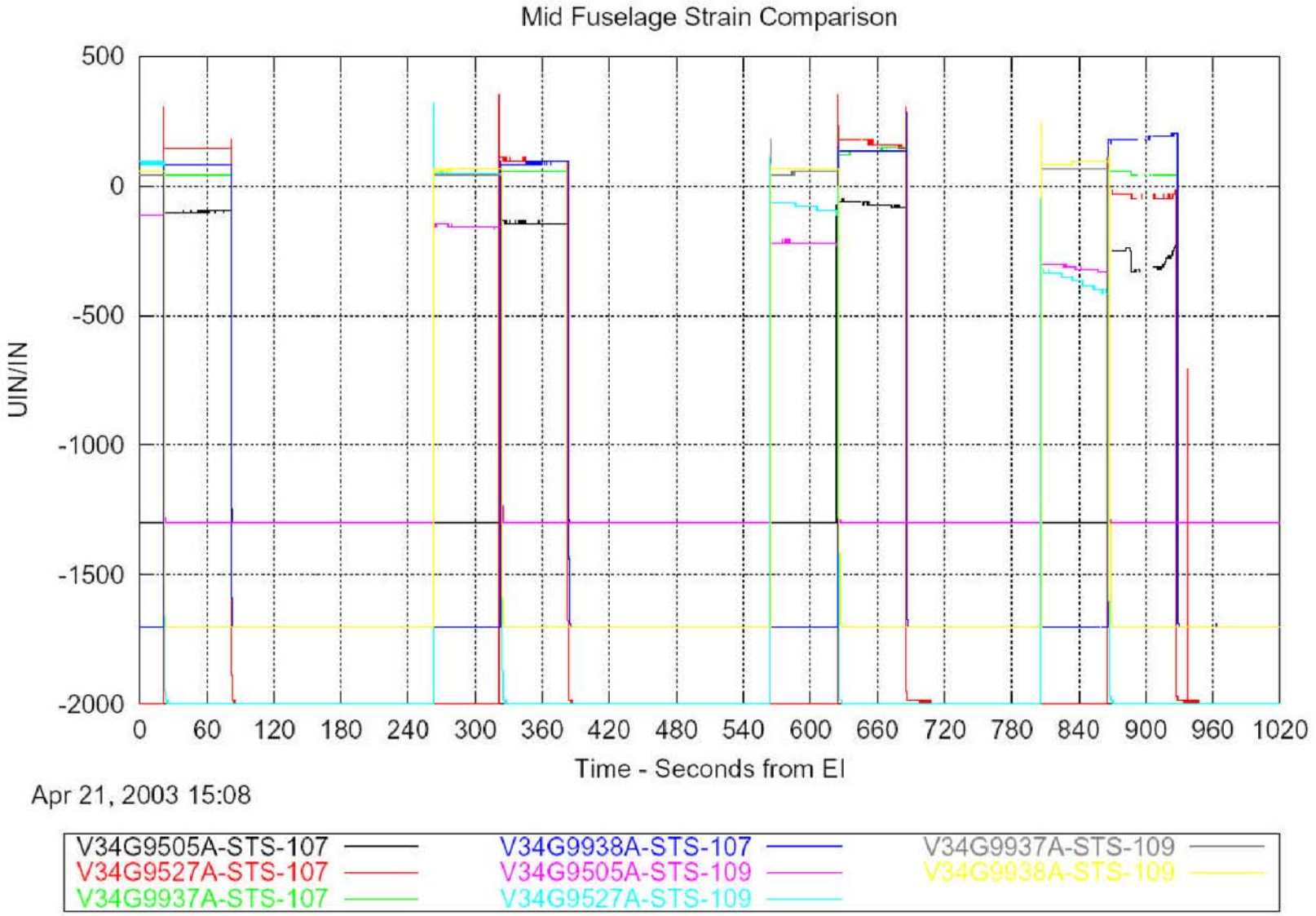
Left Wing X1040 Spar Cap Gauges Show an Anomalous Trend Initiating Between EI +500 and EI +600 Seconds



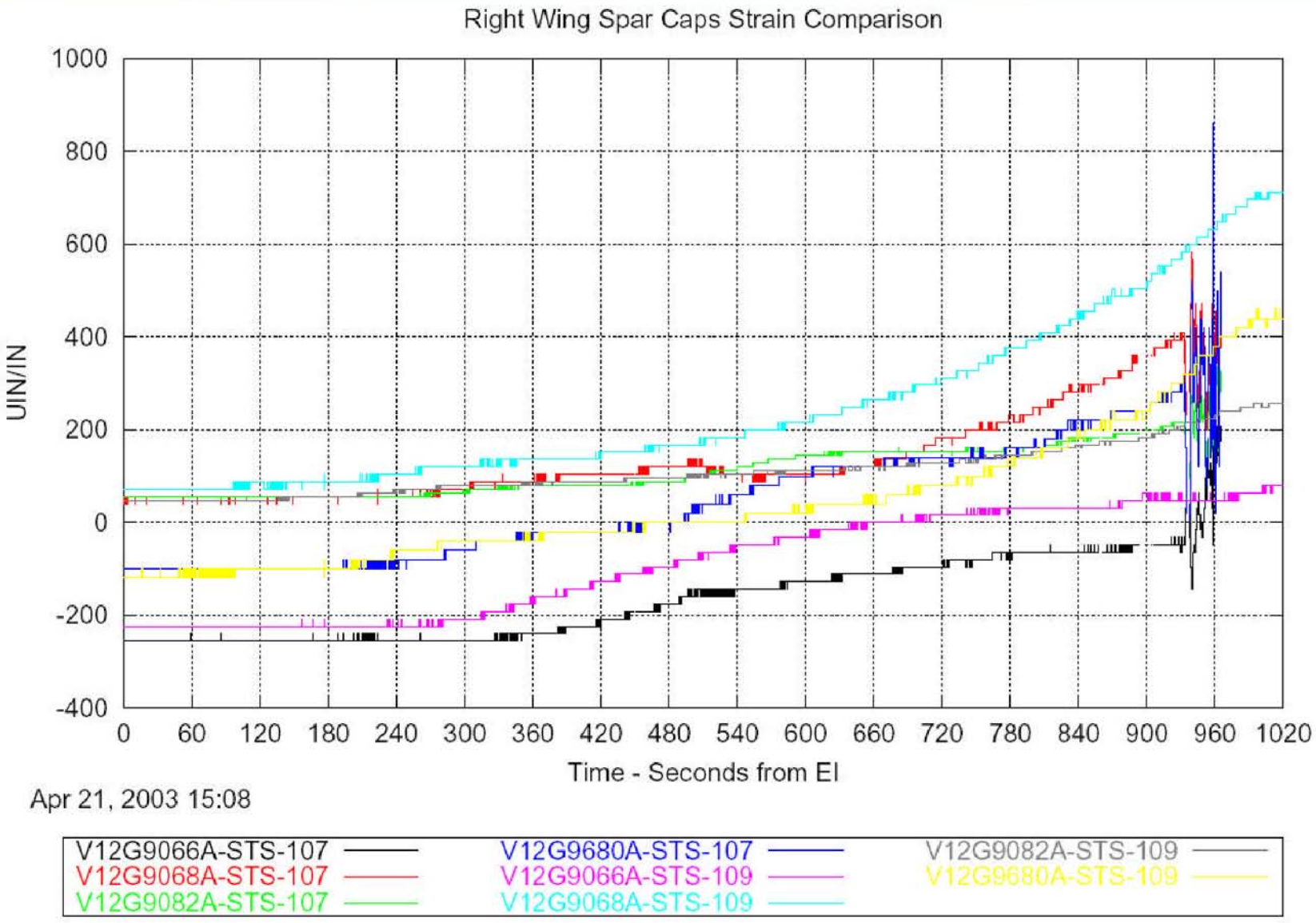
Left Wing X1040 Spar Cap Gauges Show an Anomalous Trend Initiating Between EI +500 and EI +600 Seconds



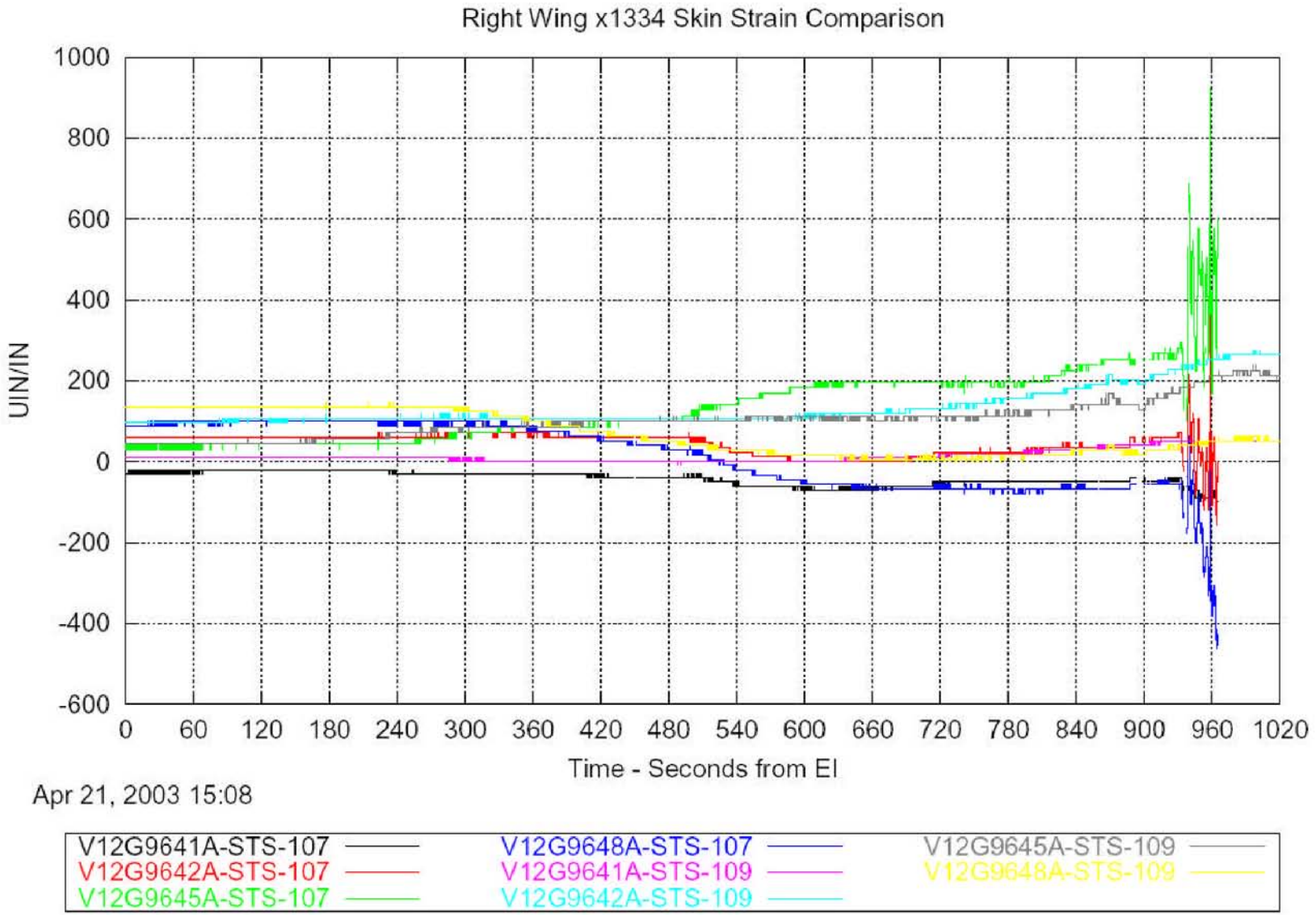
Some Mid Fuselage Gauges Show Mild Discrepancies Versus Previous Flights



Some Right Wing Spar Cap Gauges Show Mild Discrepancies Versus Previous Flights



A Number of Right Wing Skin Gauges Show Off-Nominal Trending Initiating Near EI +500 Seconds



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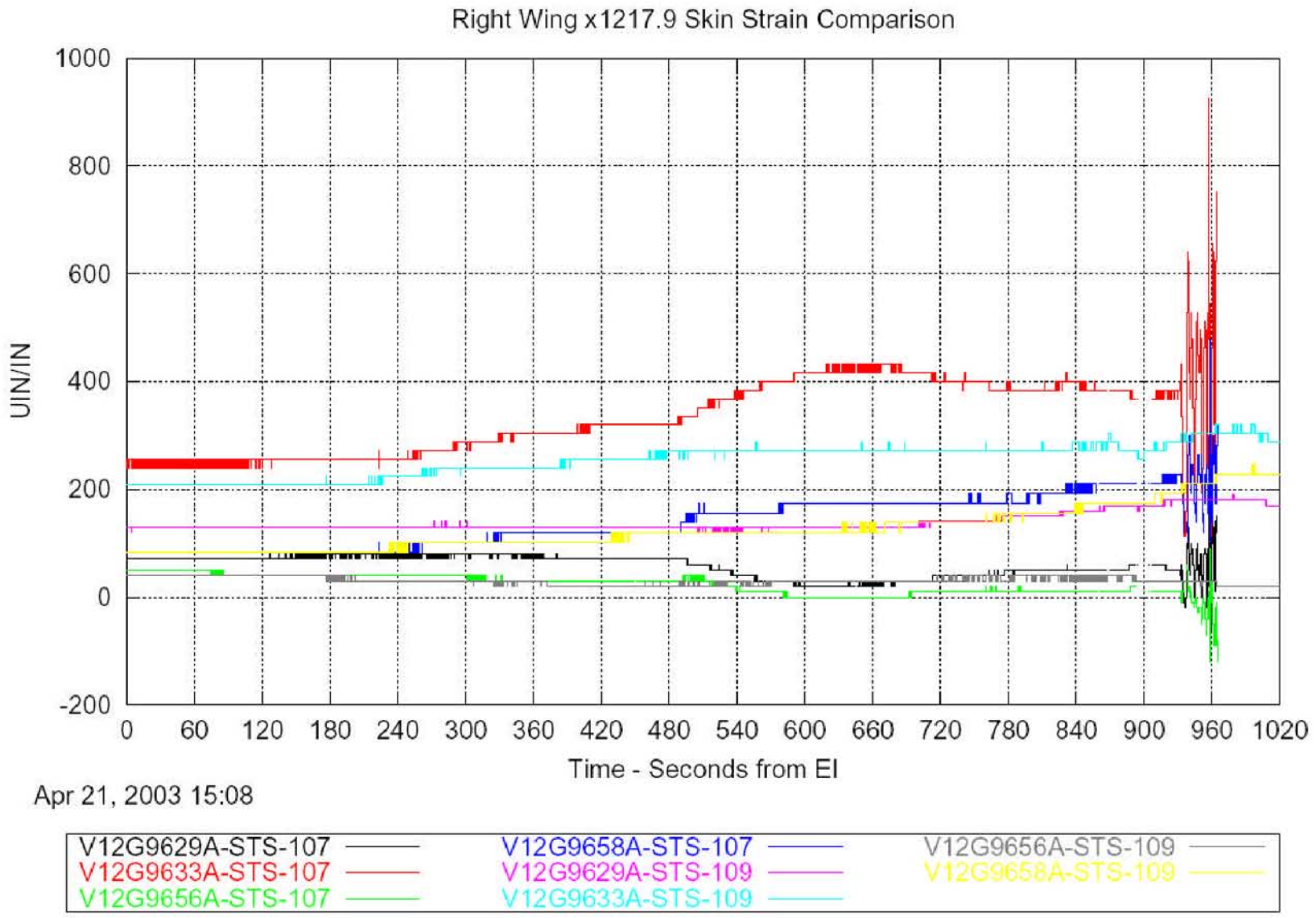

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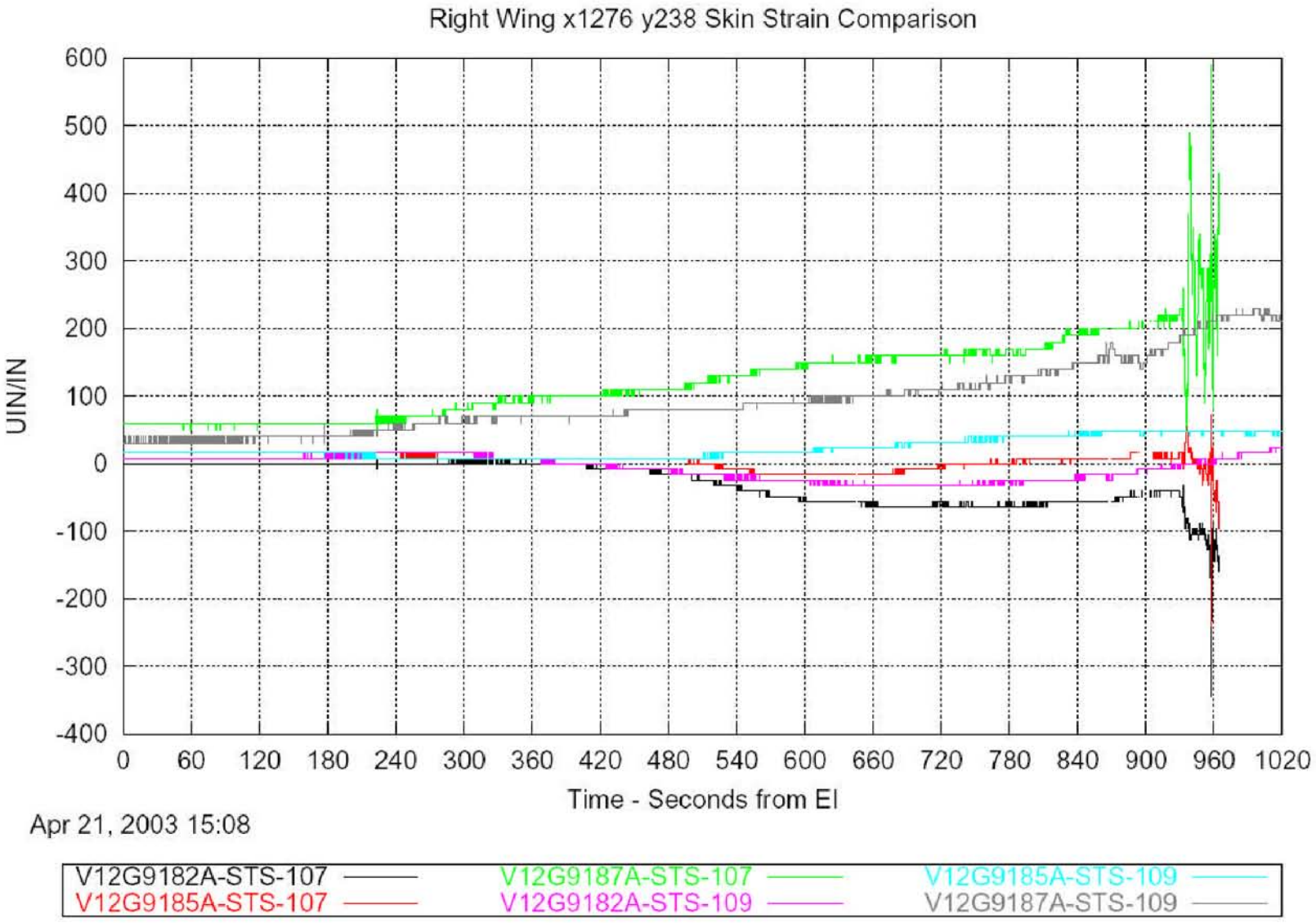

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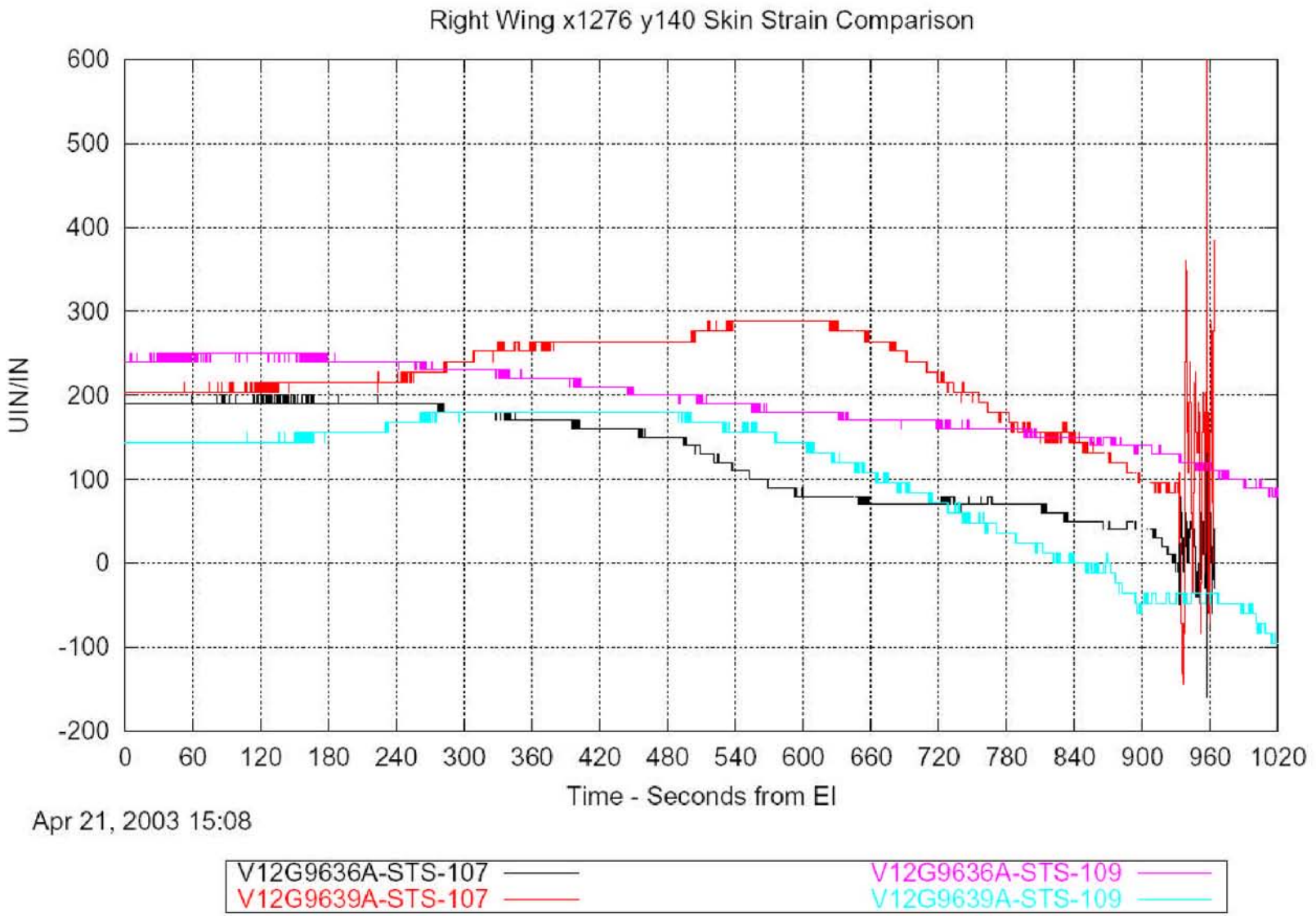
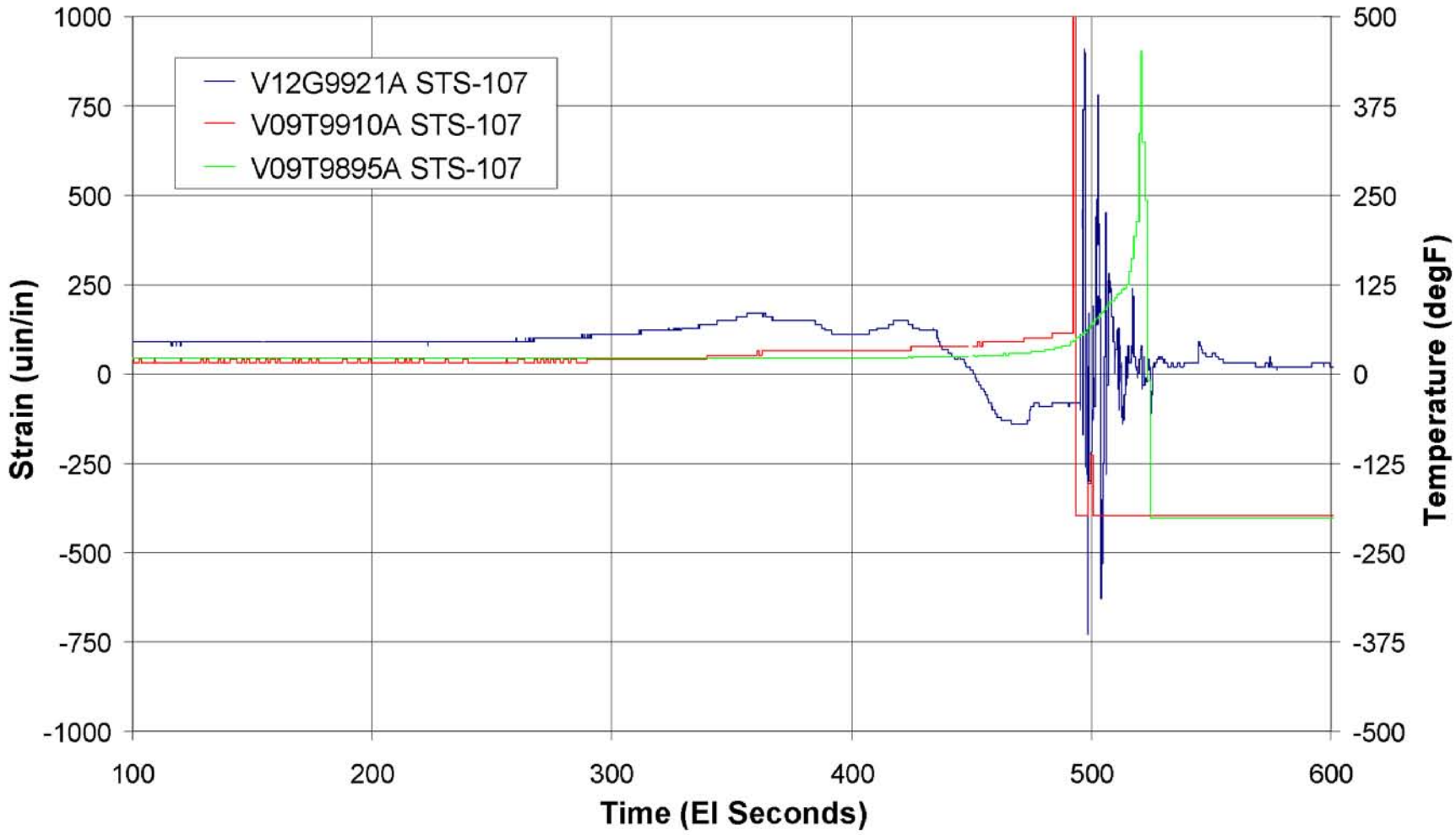


RCC Panel 9

- Three MADS gauges of particular interest near RCC Panel 9 on the Left Wing
  - One Strain gauge, Two Temperature gauges
    - V12G9921A, V09T9910A, & V09T9895A
  - Data for these three gauges was plotted together
    - Indicates failure at approximately the same time for V12G9921A and V09T9910A (~EI +495sec)
    - Later failure for V09T9895A (~EI +515sec)
  - Continued analysis is underway for this data.

RCC Panel 9 Strain and Temperature Gauges

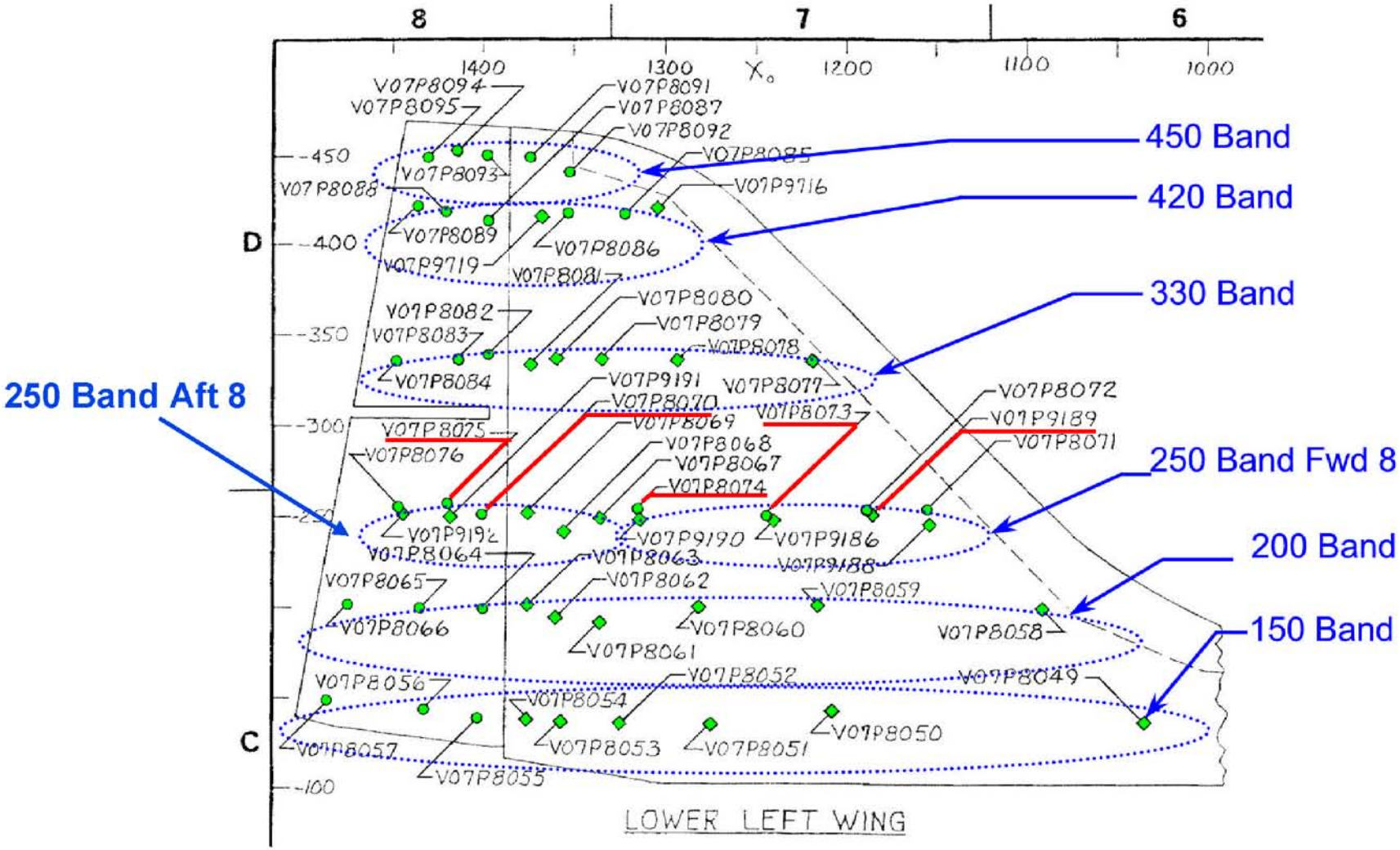


STS-107 MADS Pressure Data

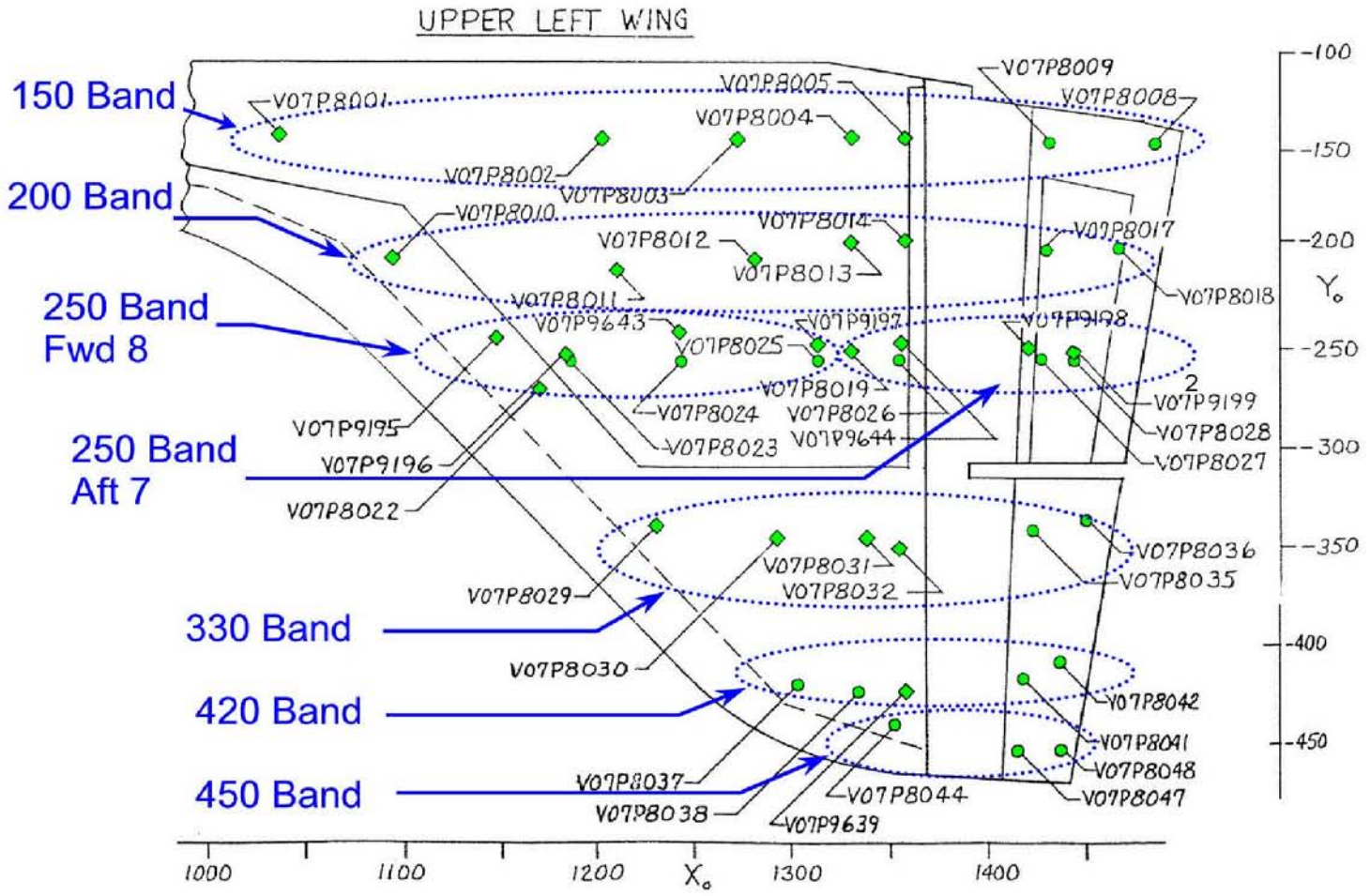
Summary

- Ascent
  - Pressure transducers are sized for ascent load environments
  - Pressures were compared within Y-station family and with past flights
  - Pressure tap V07P8073 appears to have been hit at 84.4 seconds
  - Pressure tap V07P8074 is "out-of-family" after 82 seconds as compared to past flights
  - Pressure taps V07P8070, V07P8075 and V07P9189 have similar strange behavior around 102-104 seconds
  - Remaining pressure taps show no significant events
- Entry
  - Pressures also compared within Y-station and past flights
  - Data review typically made in the Mach 3.5 to 0.6 range for instrument functionality and "signature" comparison
  - Pressures generally show intermittent data spikes/dropouts in the 480-660 sec and 930-970 sec timeframe

Lower Left Wing Y-Station Taps

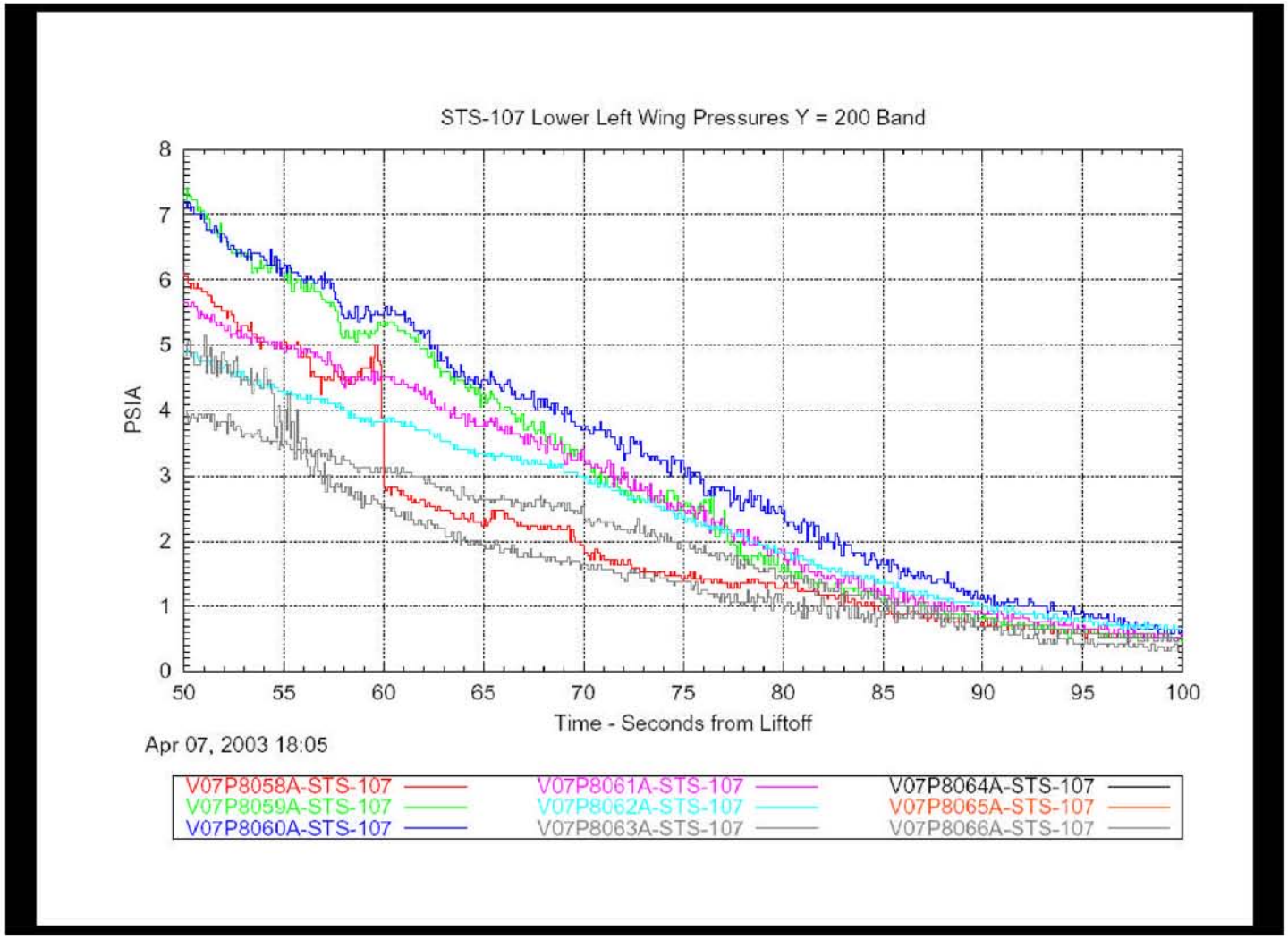


Upper Left Wing Y-Station Taps

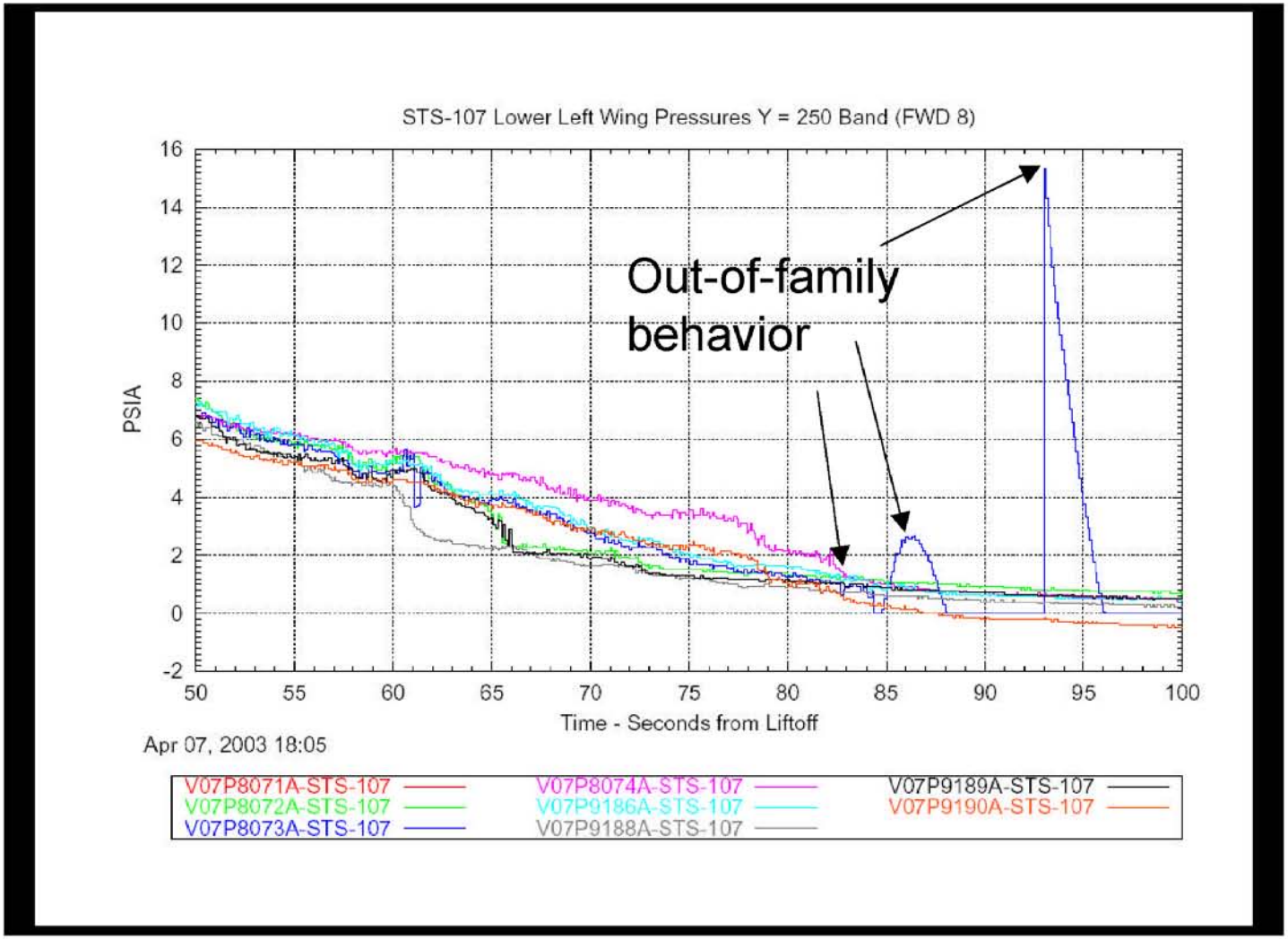


STS-107 MADS Pressure Data Ascent

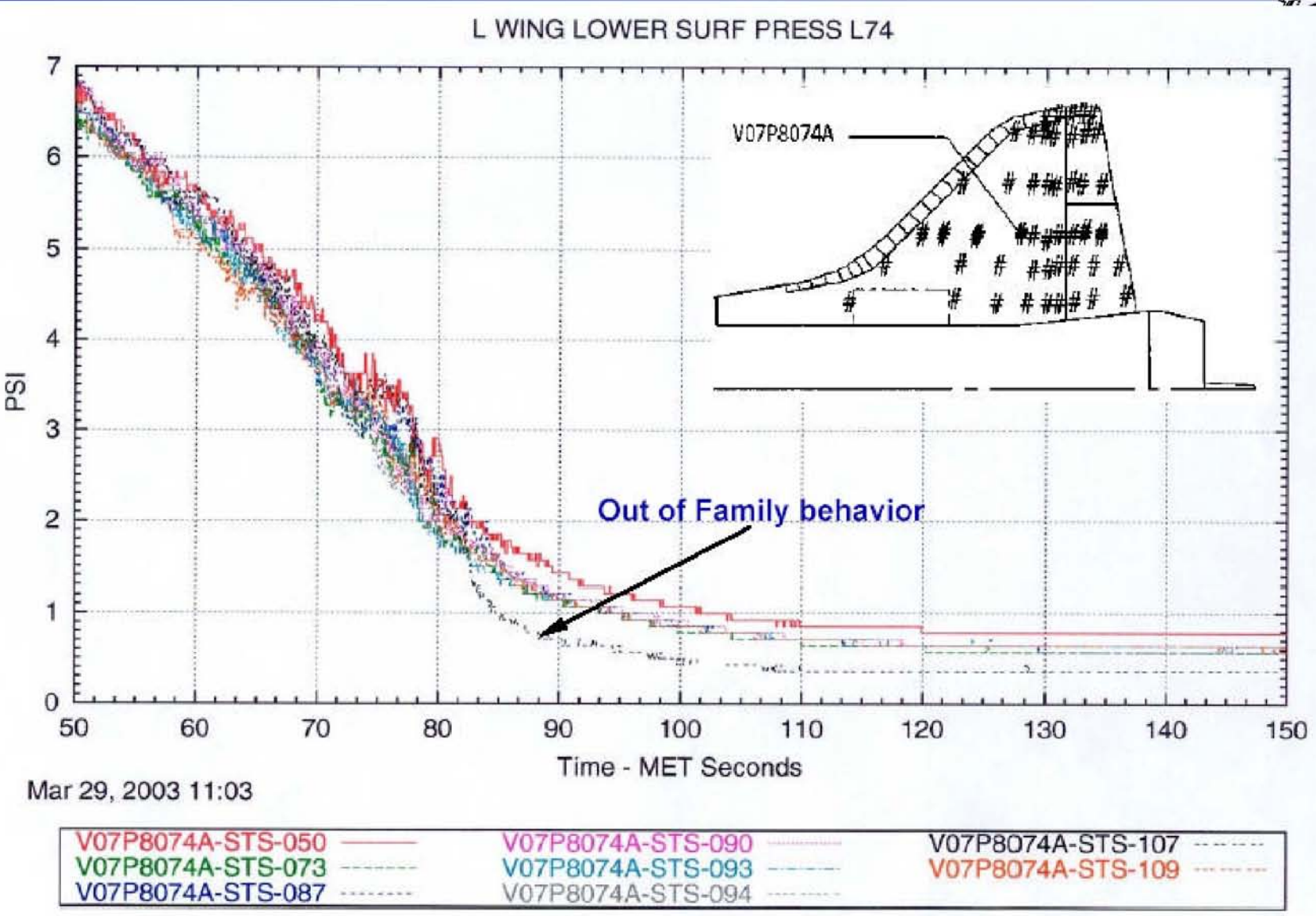
Lower Left Wing Y=200 Taps



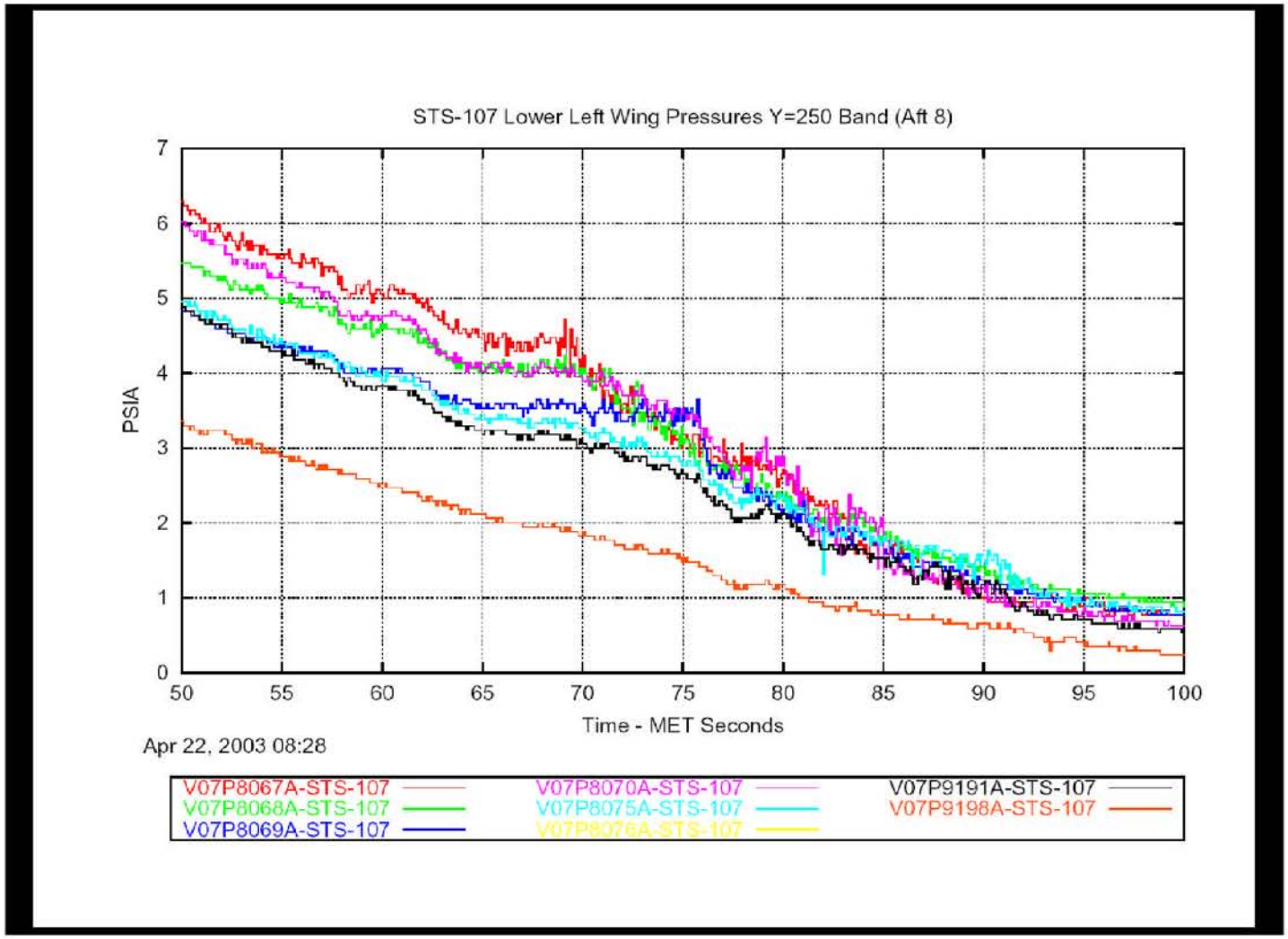
Lower Left Wing Y=250 Taps (Fwd 8)



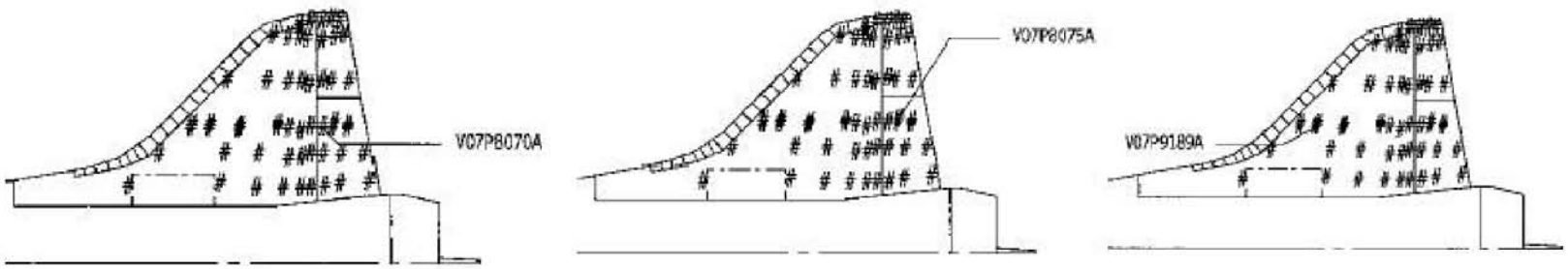
Lower Left Wing Y=250 Tap V07P8074A (Fwd 8)

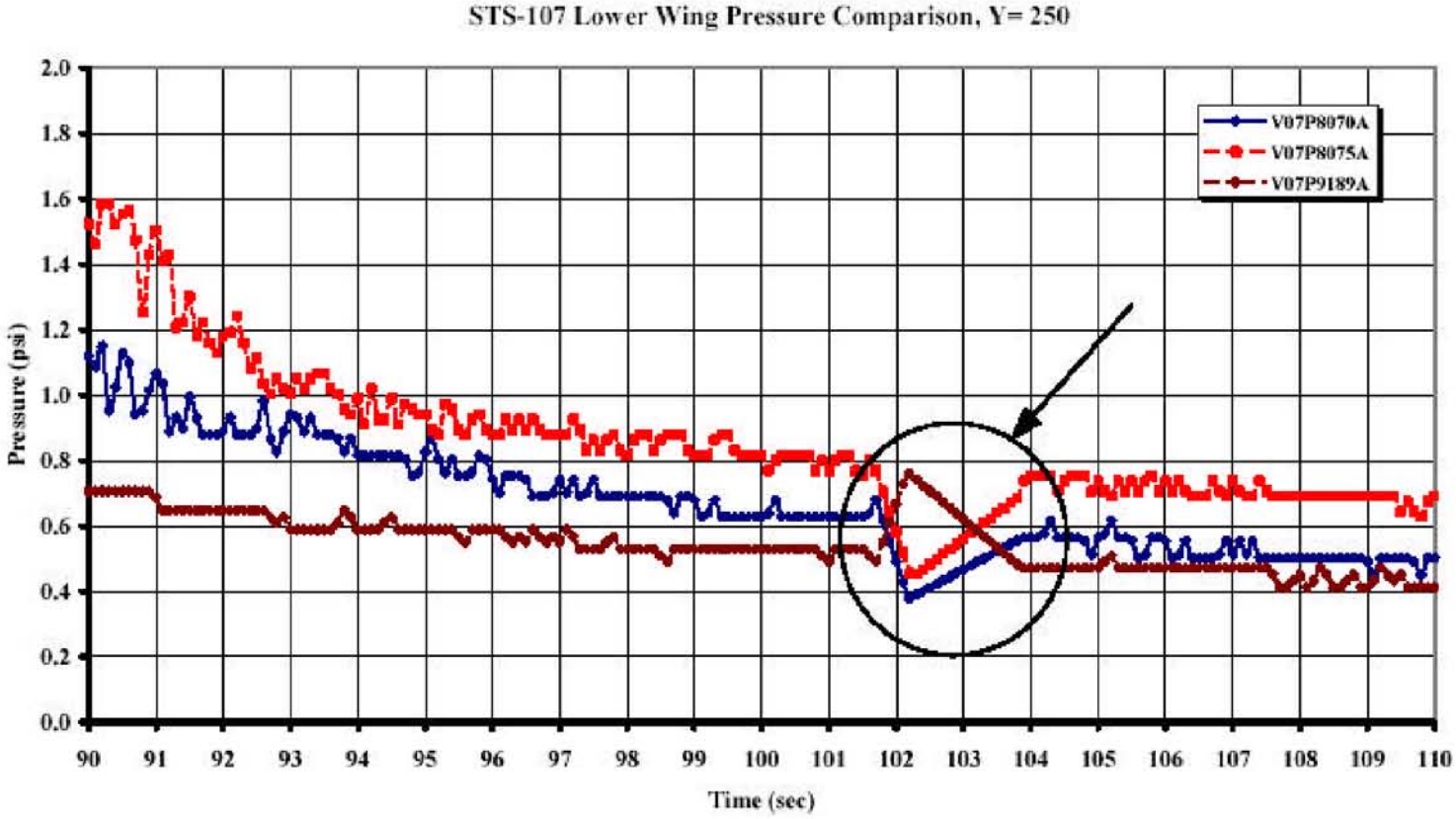


Lower Left Wing Y=250 Taps (Aft 8)



Three Lower Left Wing Y=250 Taps Have Similar Behavior at 102 Seconds

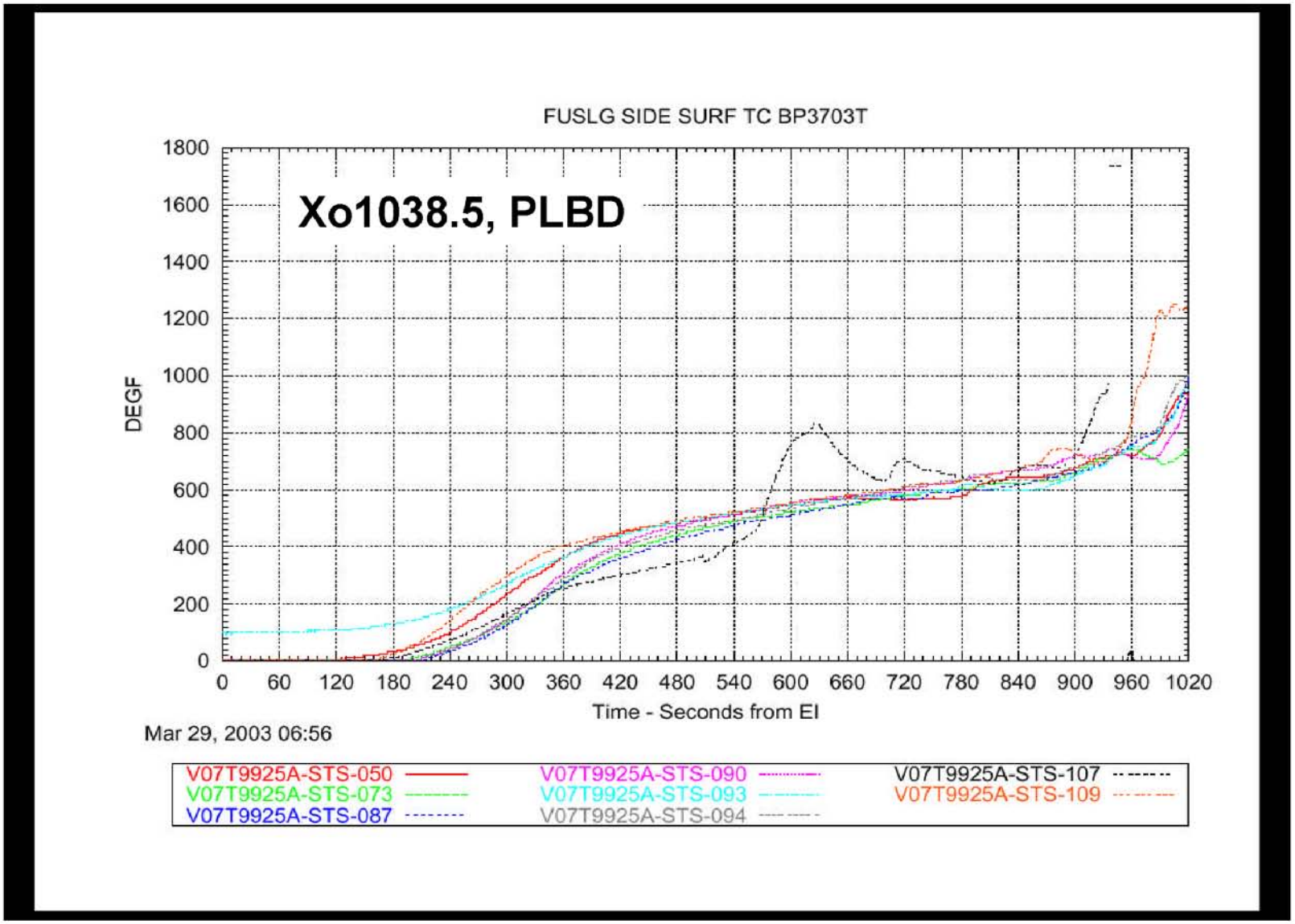




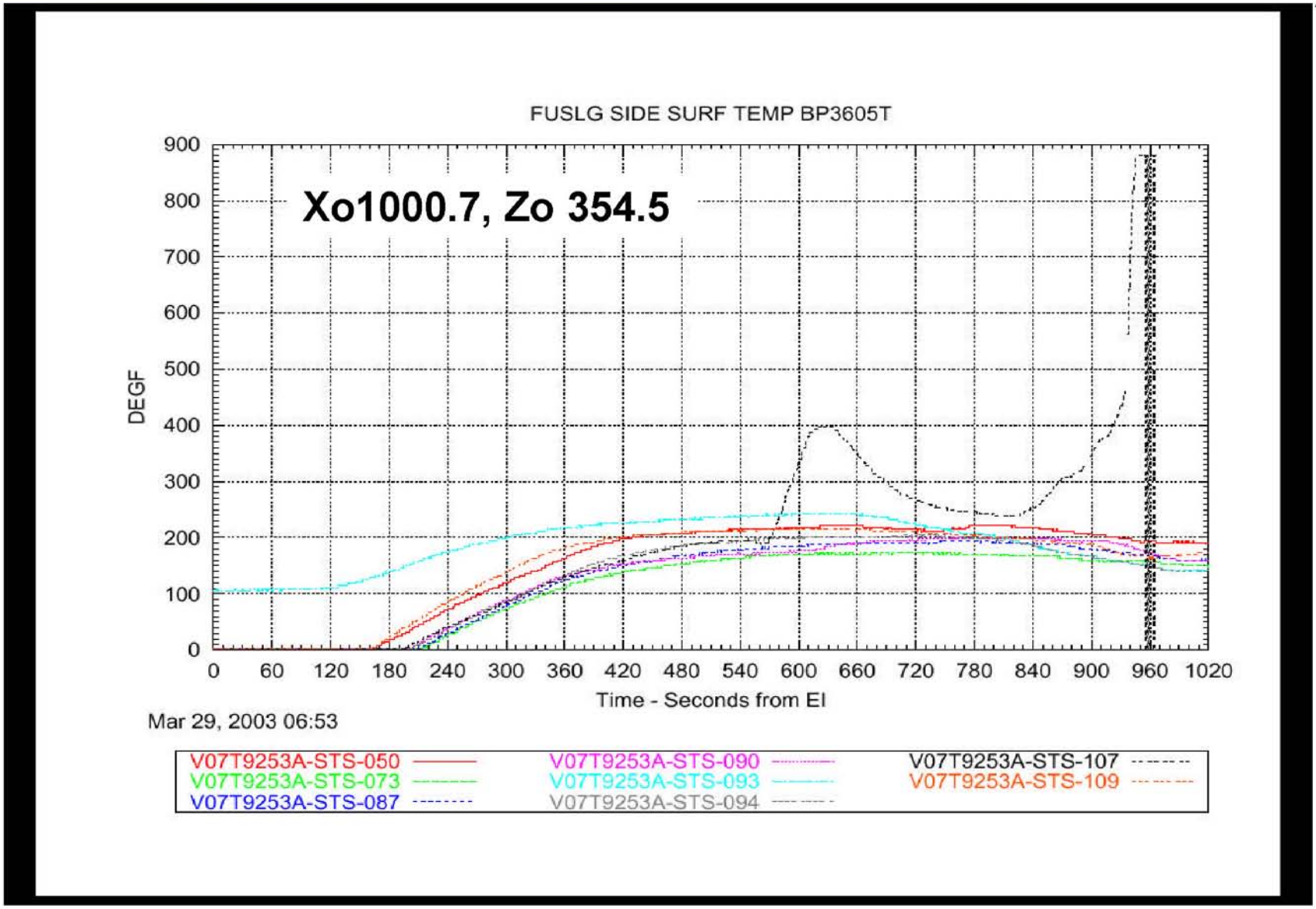
Back-up Data

Back-up Data, Temperature

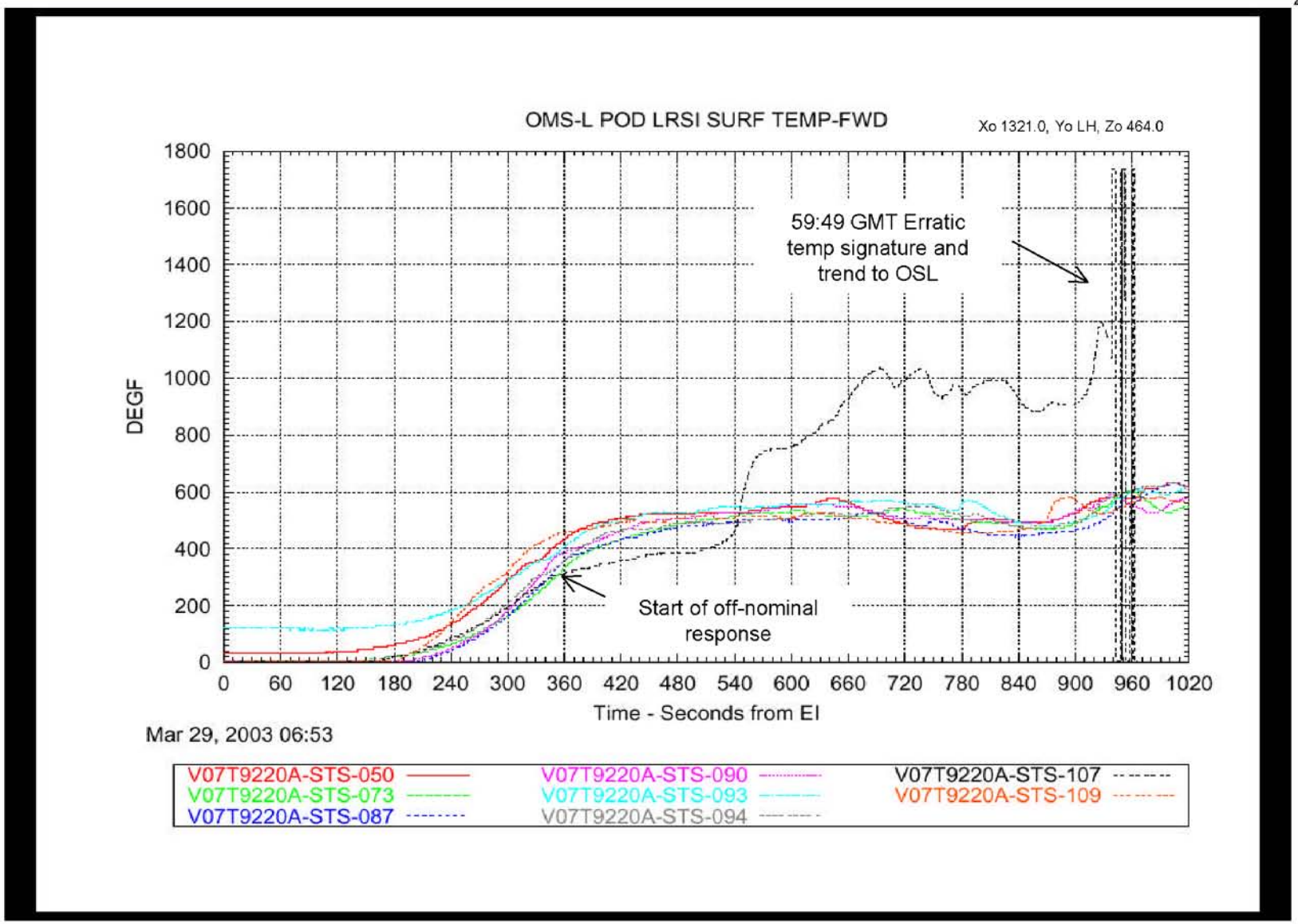
Comparison Left Side Surface - Entry



Comparison Left Side Surface - Entry

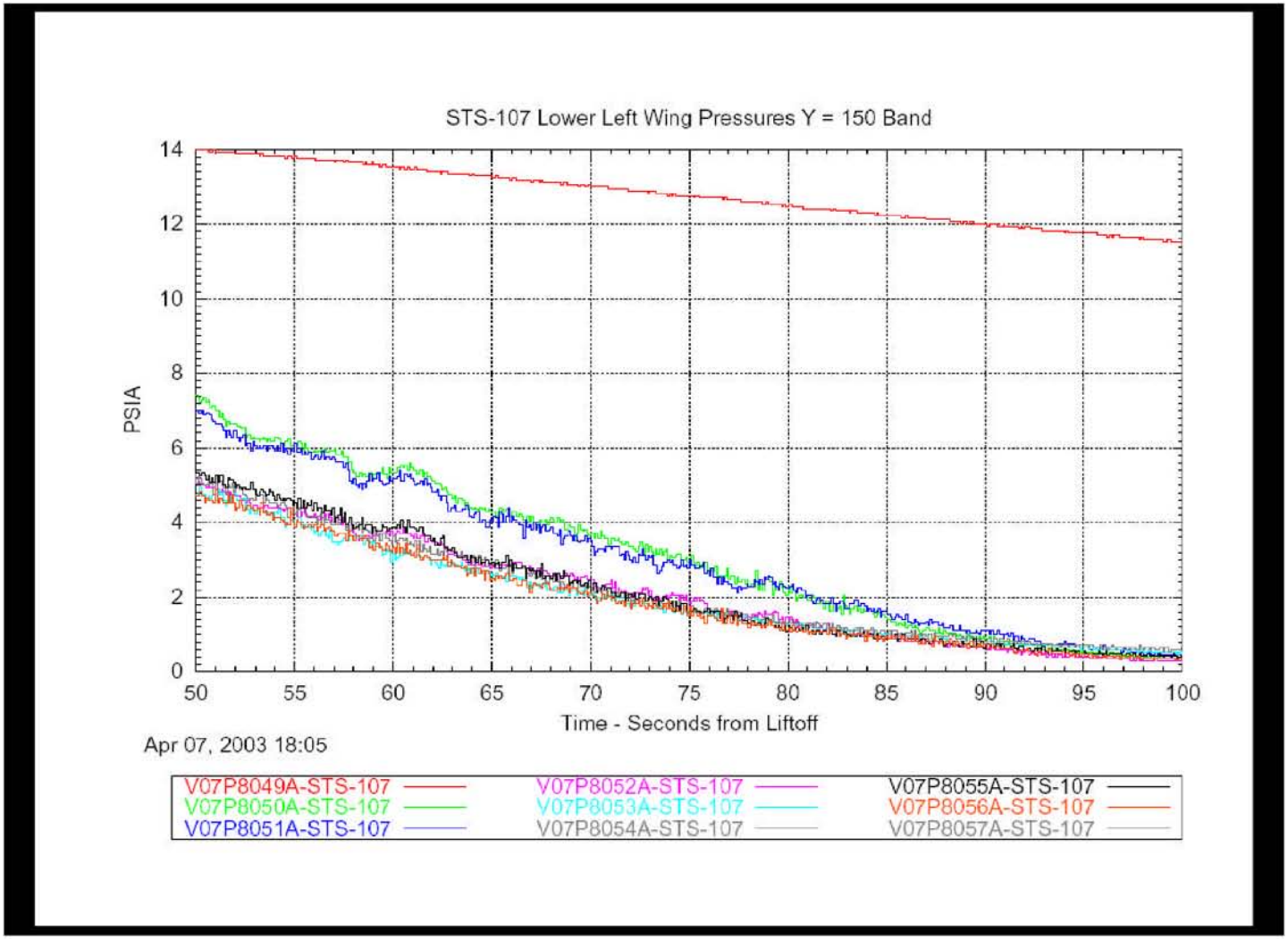


Comparison Left Pod Surface Temp Response

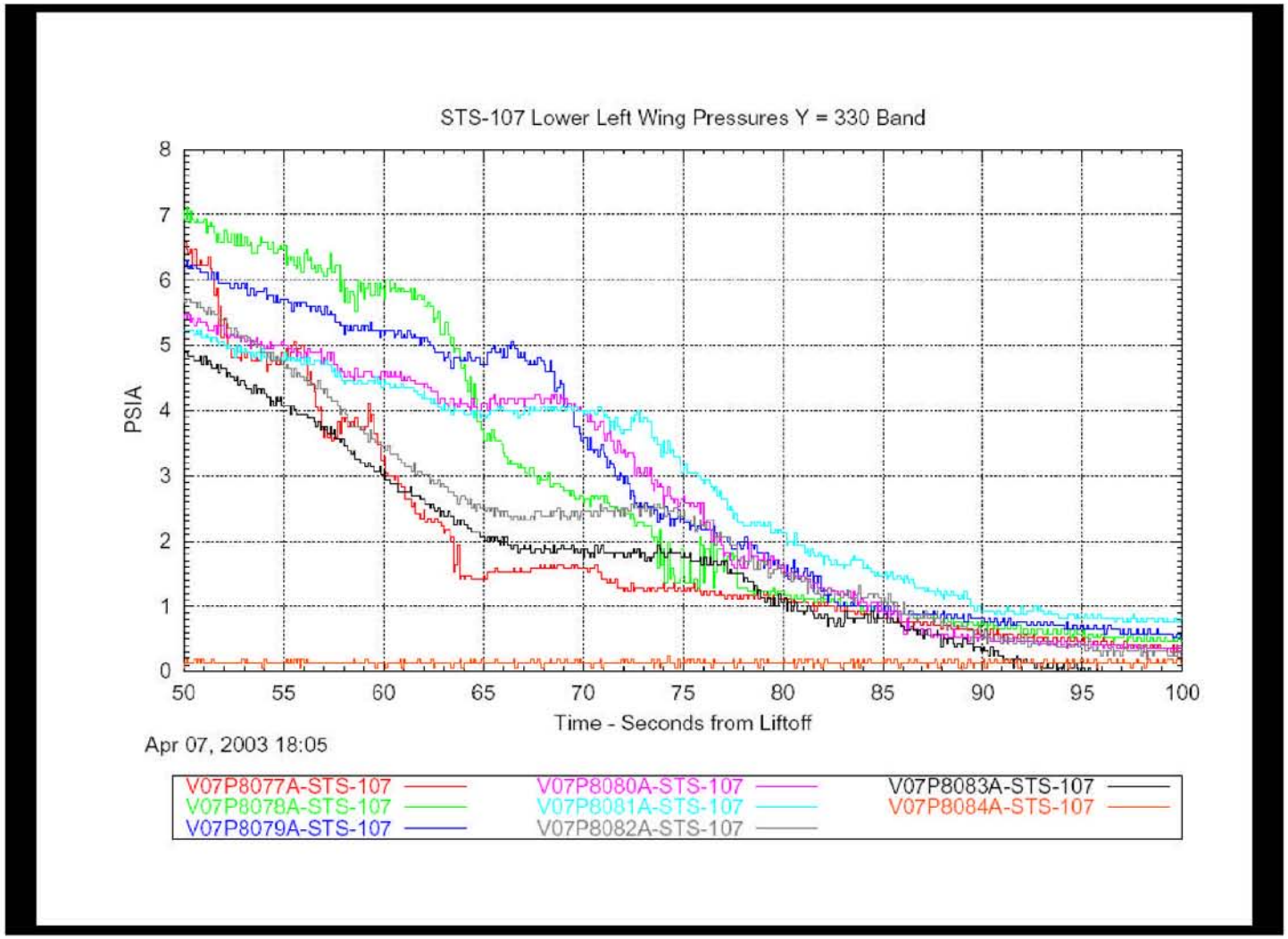


Back-up Data, Pressure

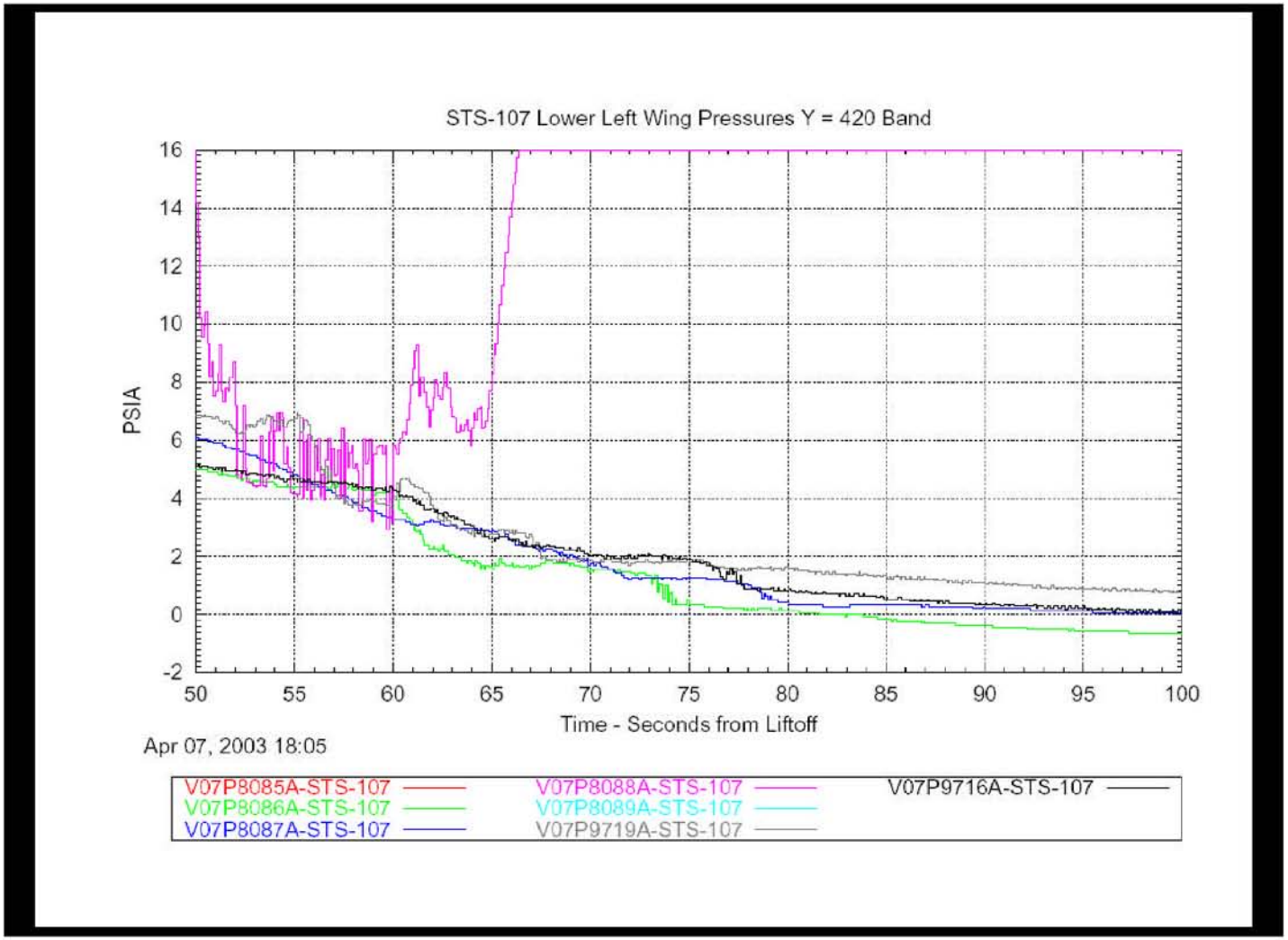
Lower Left Wing Y=150 Taps



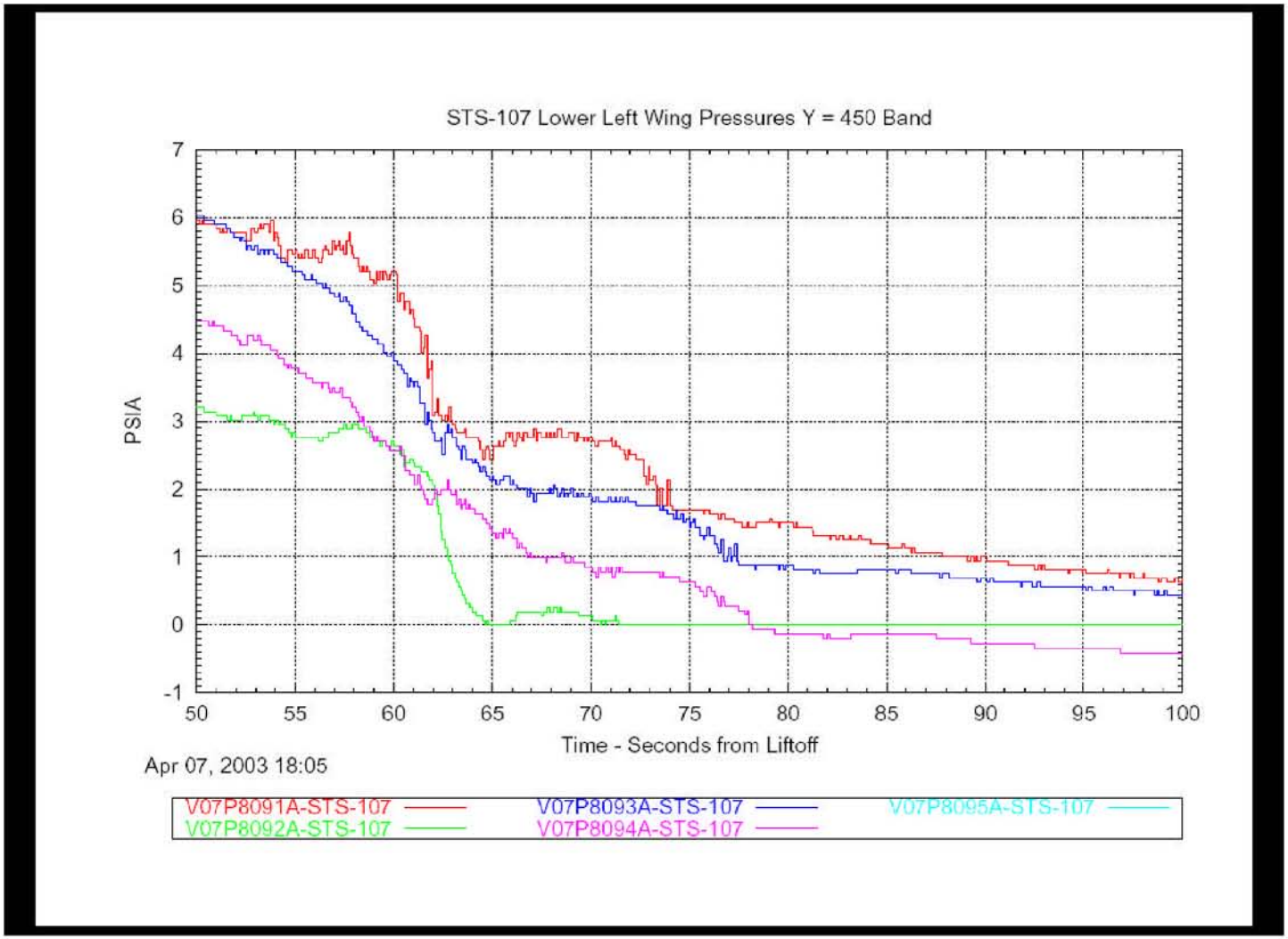
Lower Left Wing Y=330 Taps



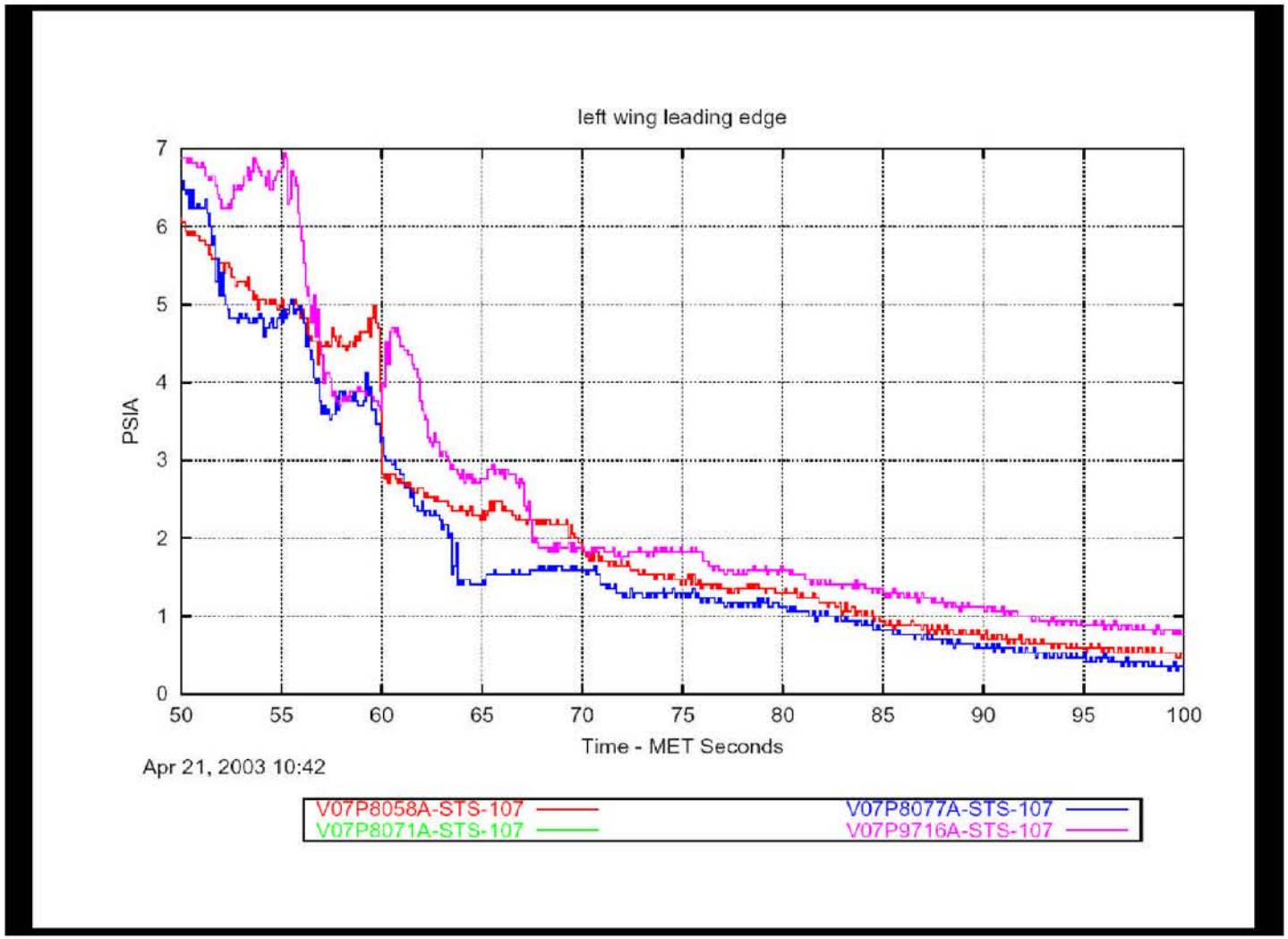
Lower Left Wing Y=420 Taps



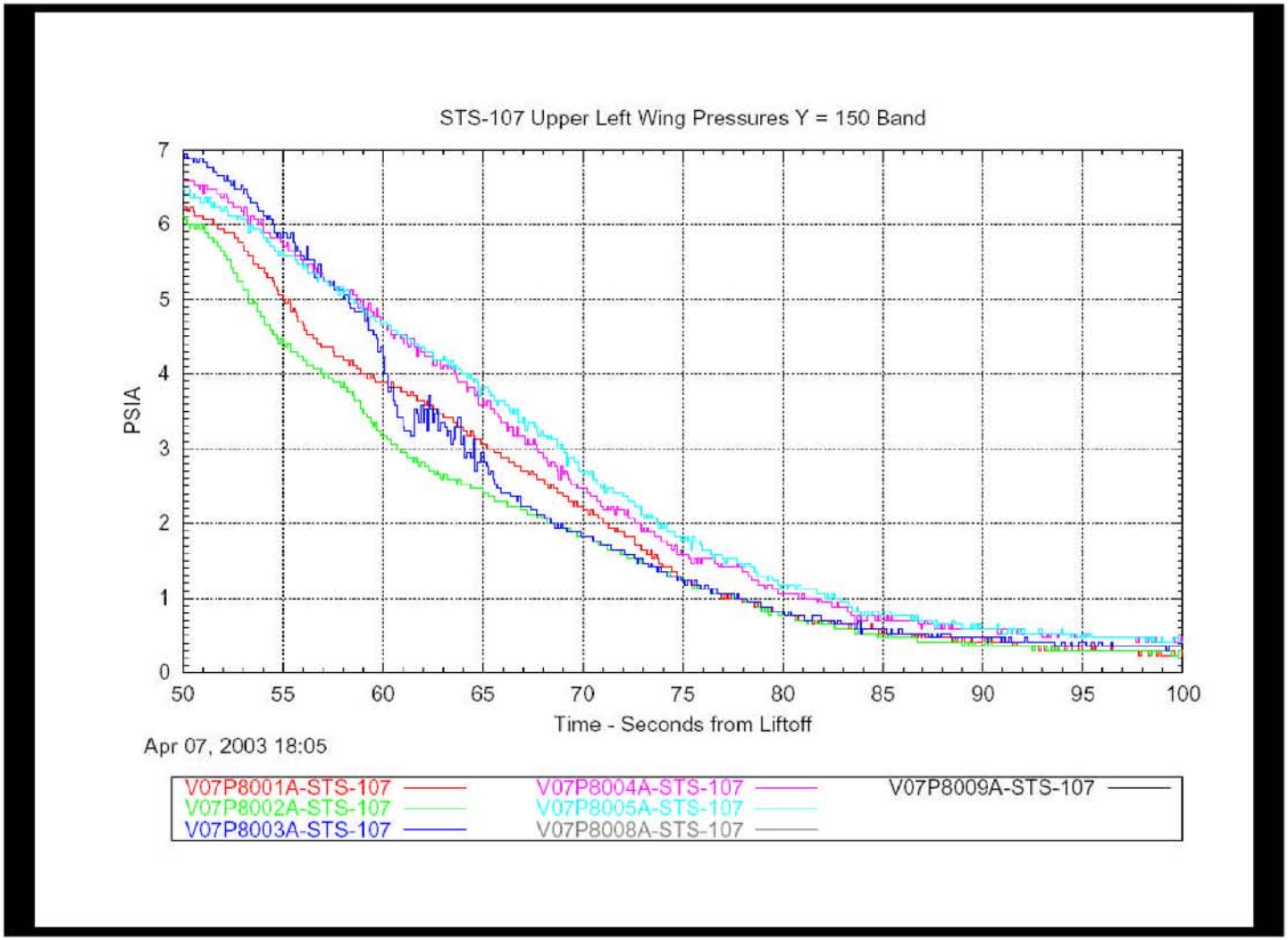
Lower Left Wing Y=450 Taps



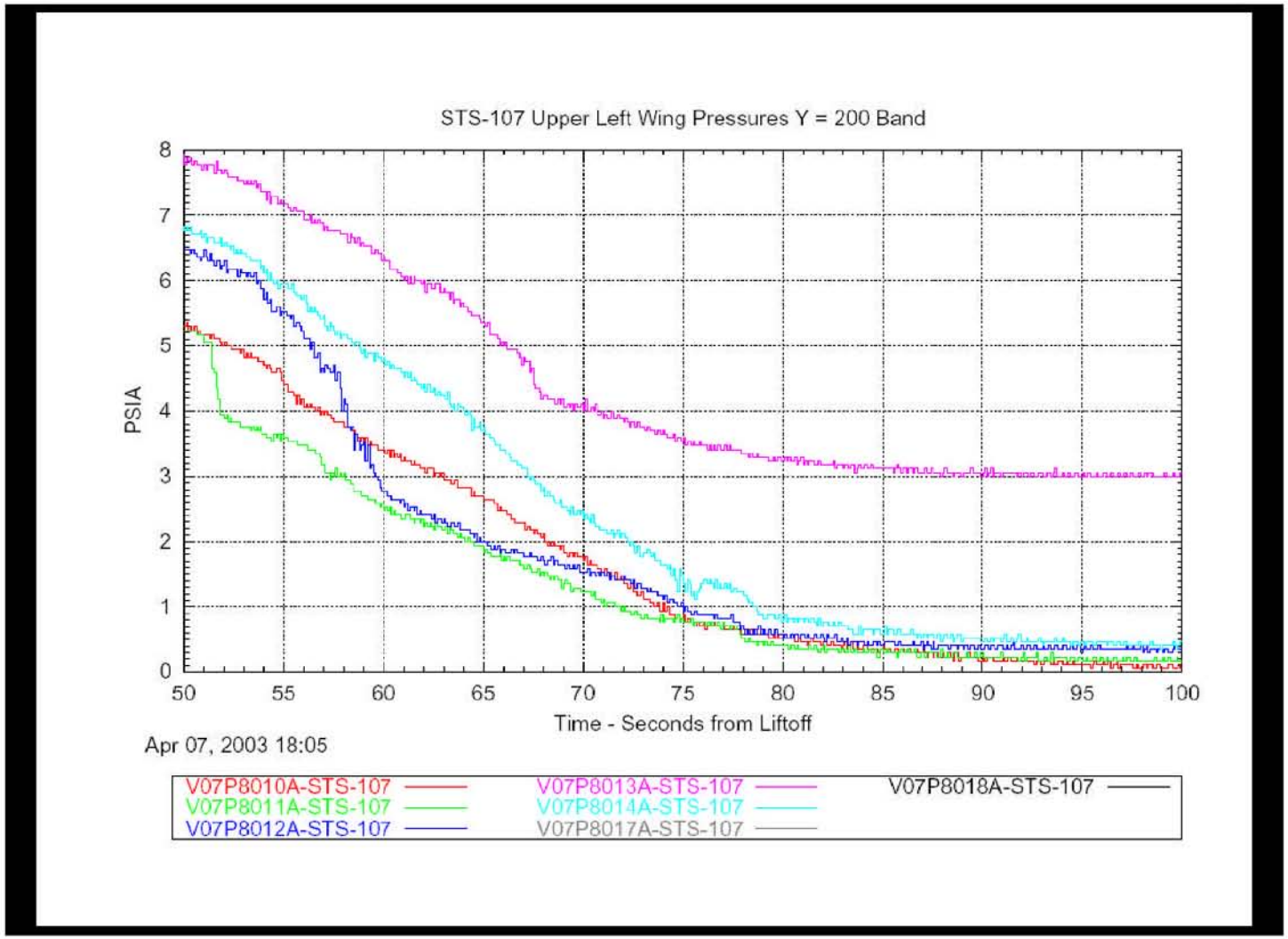
Left Wing Leading Edge (Lower) Taps



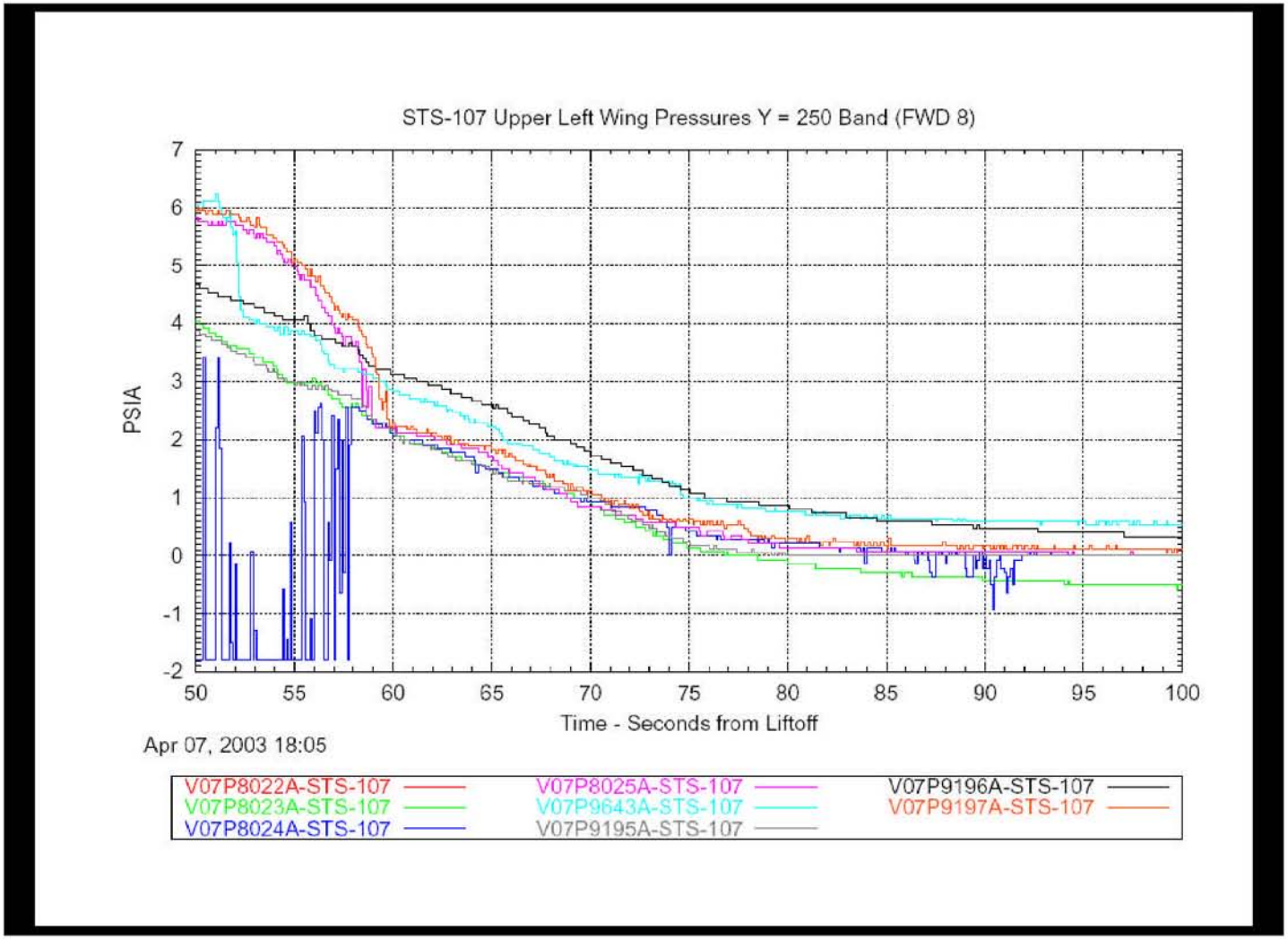
Upper Left Wing Y=150 Taps



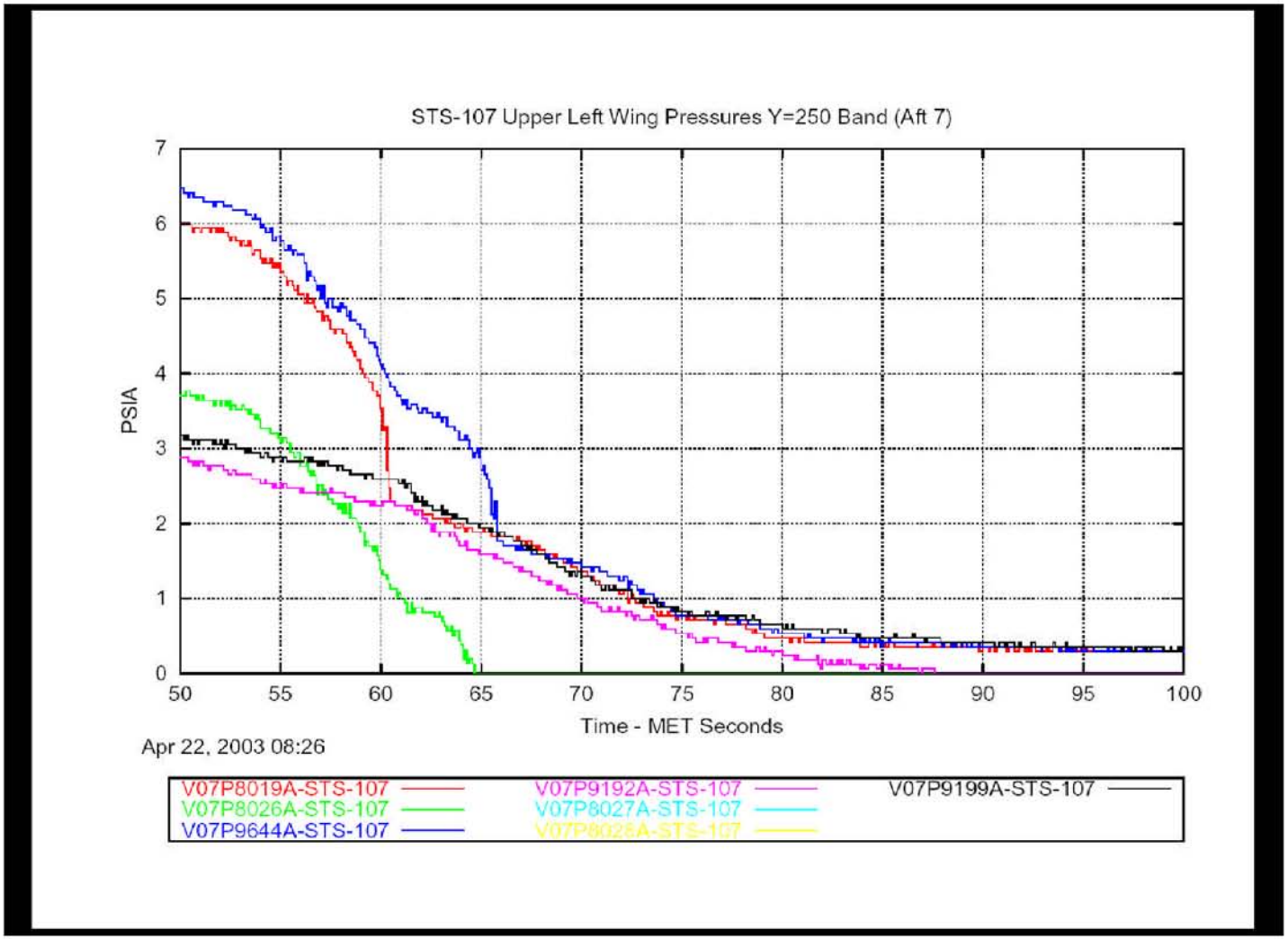
Upper Left Wing Y=200 Taps



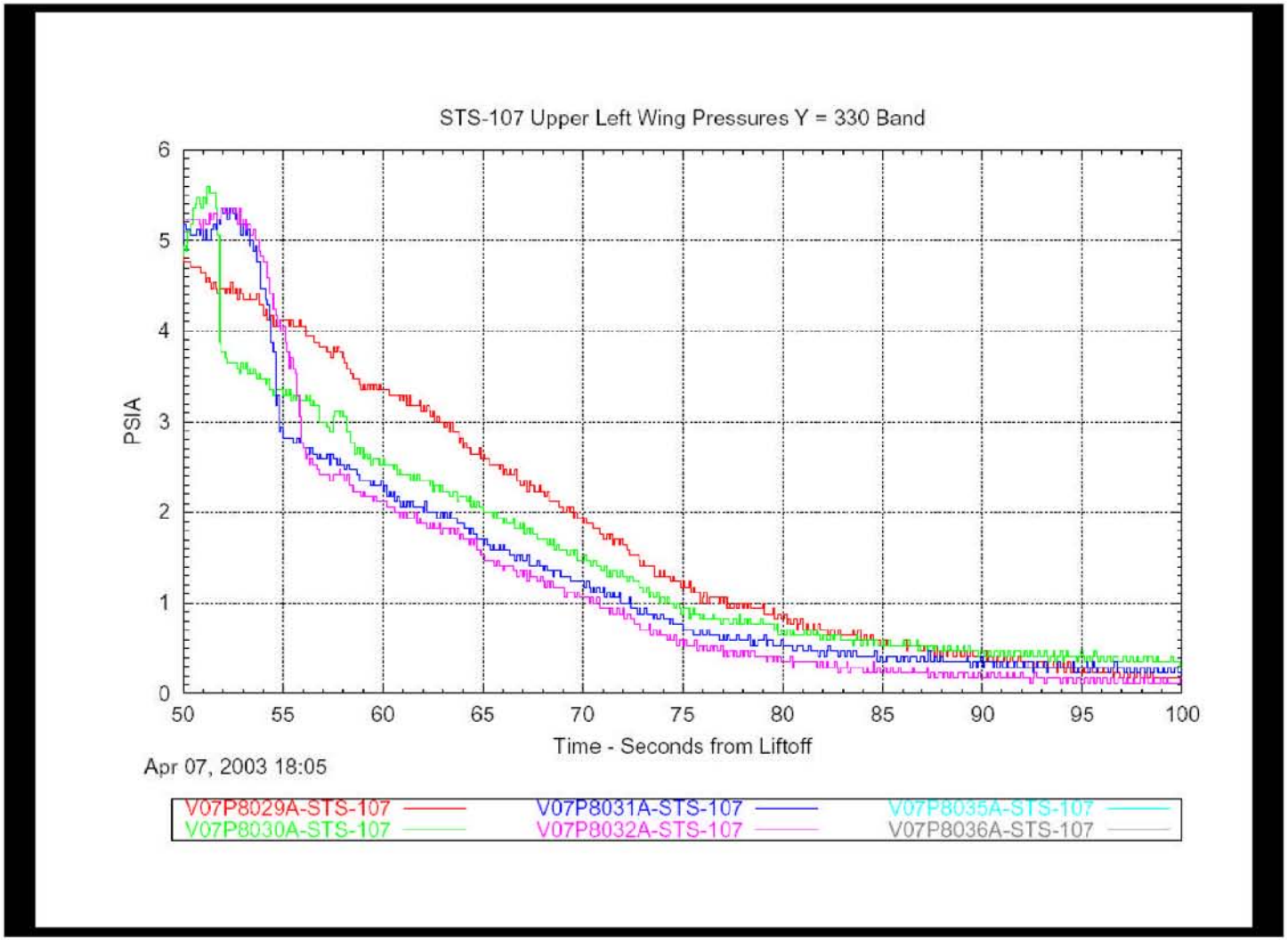
Upper Left Wing Y=250 Taps (Fwd 8)



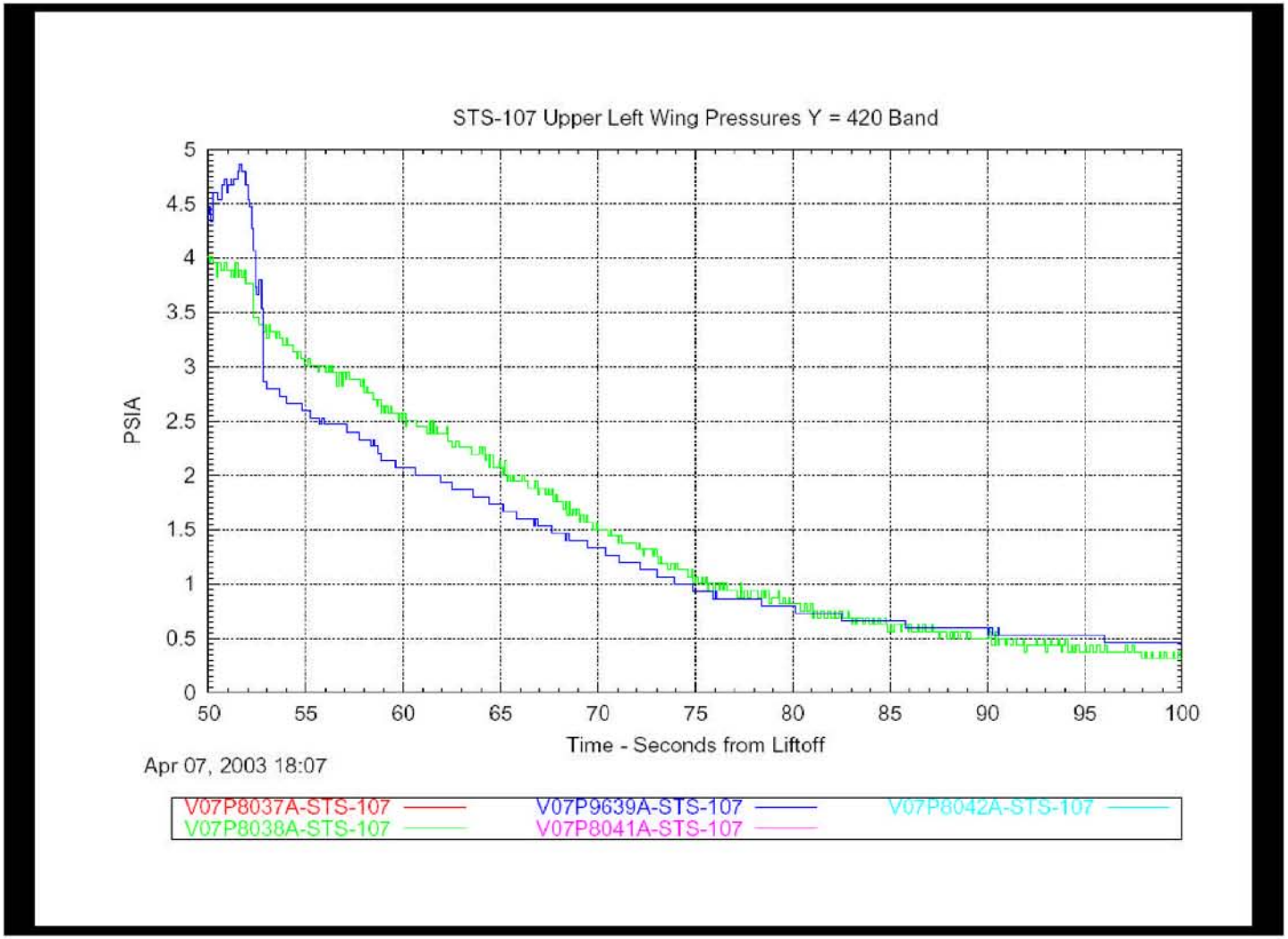
Upper Left Wing Y=250 Taps (Aft 7)



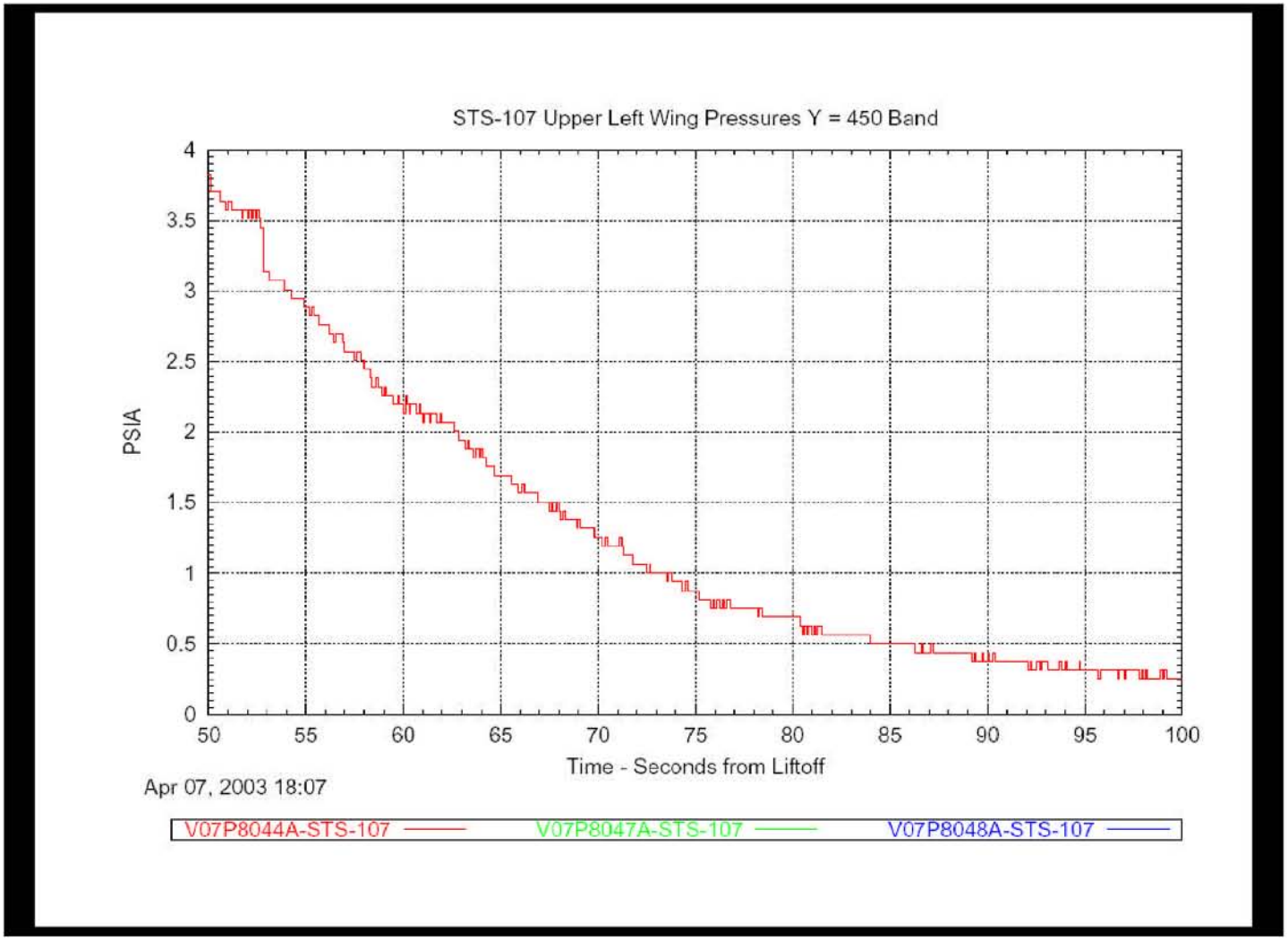
Upper Left Wing Y=330 Taps



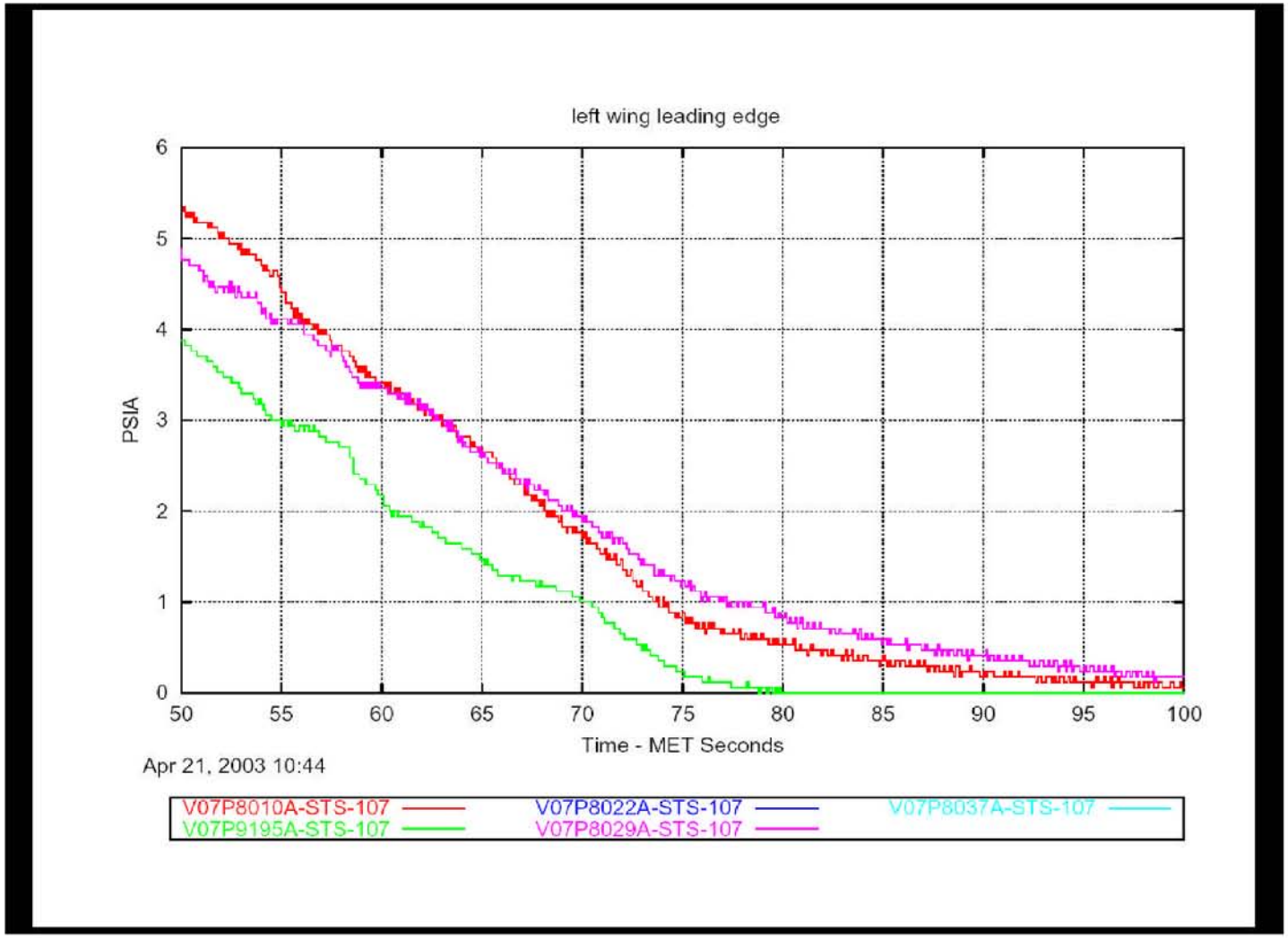
Upper Left Wing Y=420 Taps



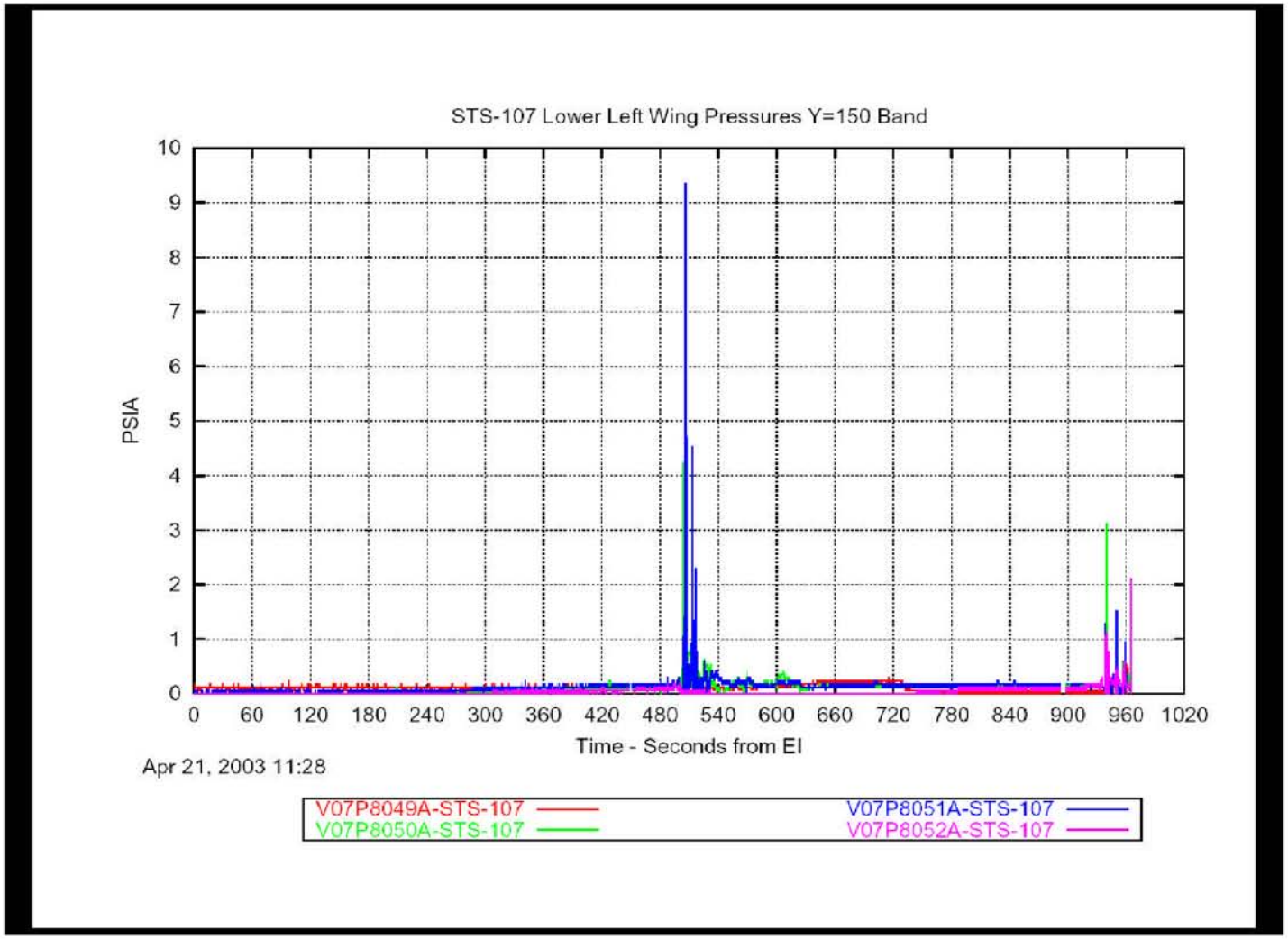
Upper Left Wing Y=450 Taps



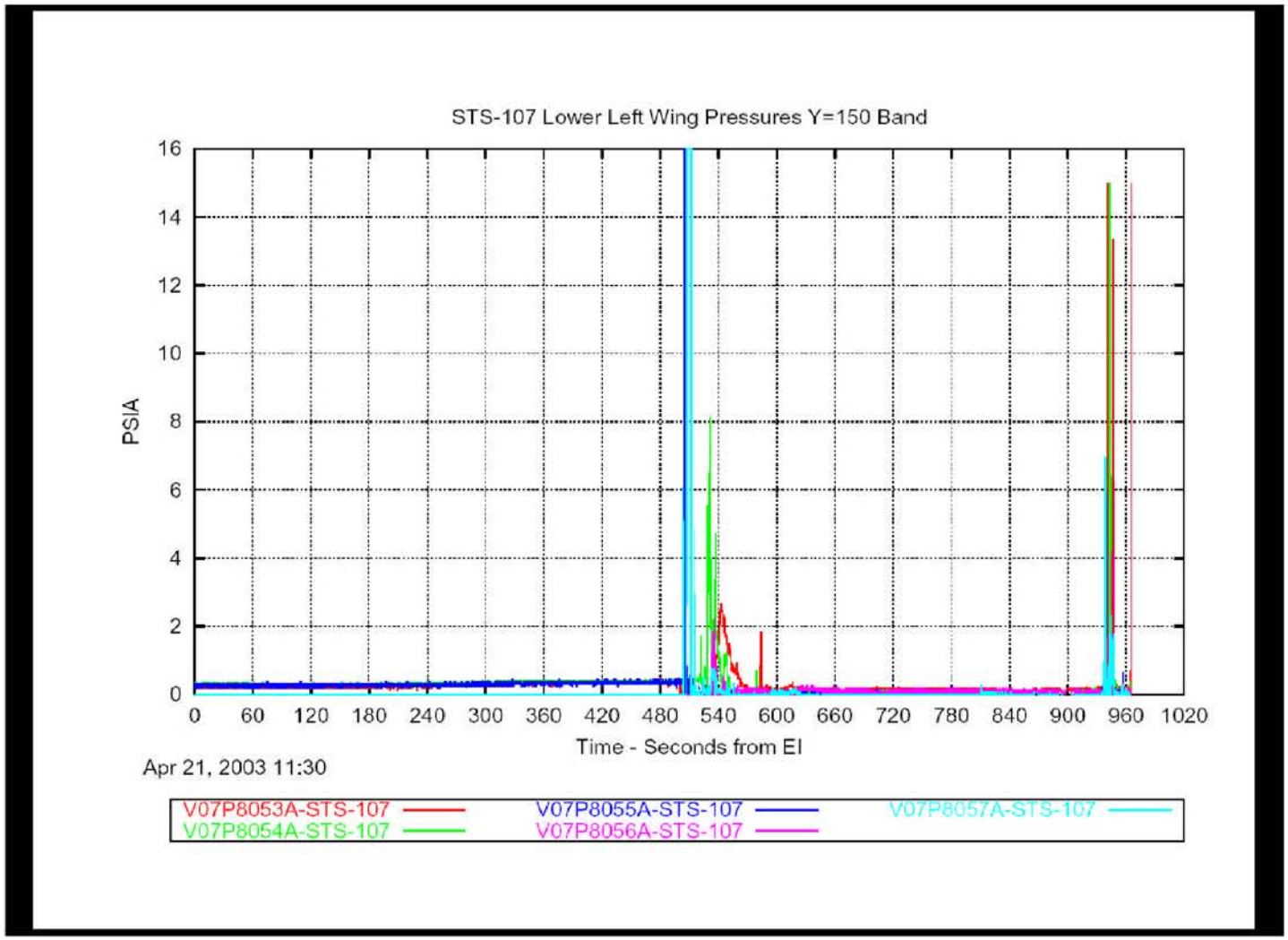
Left Wing Leading Edge (Upper) Taps



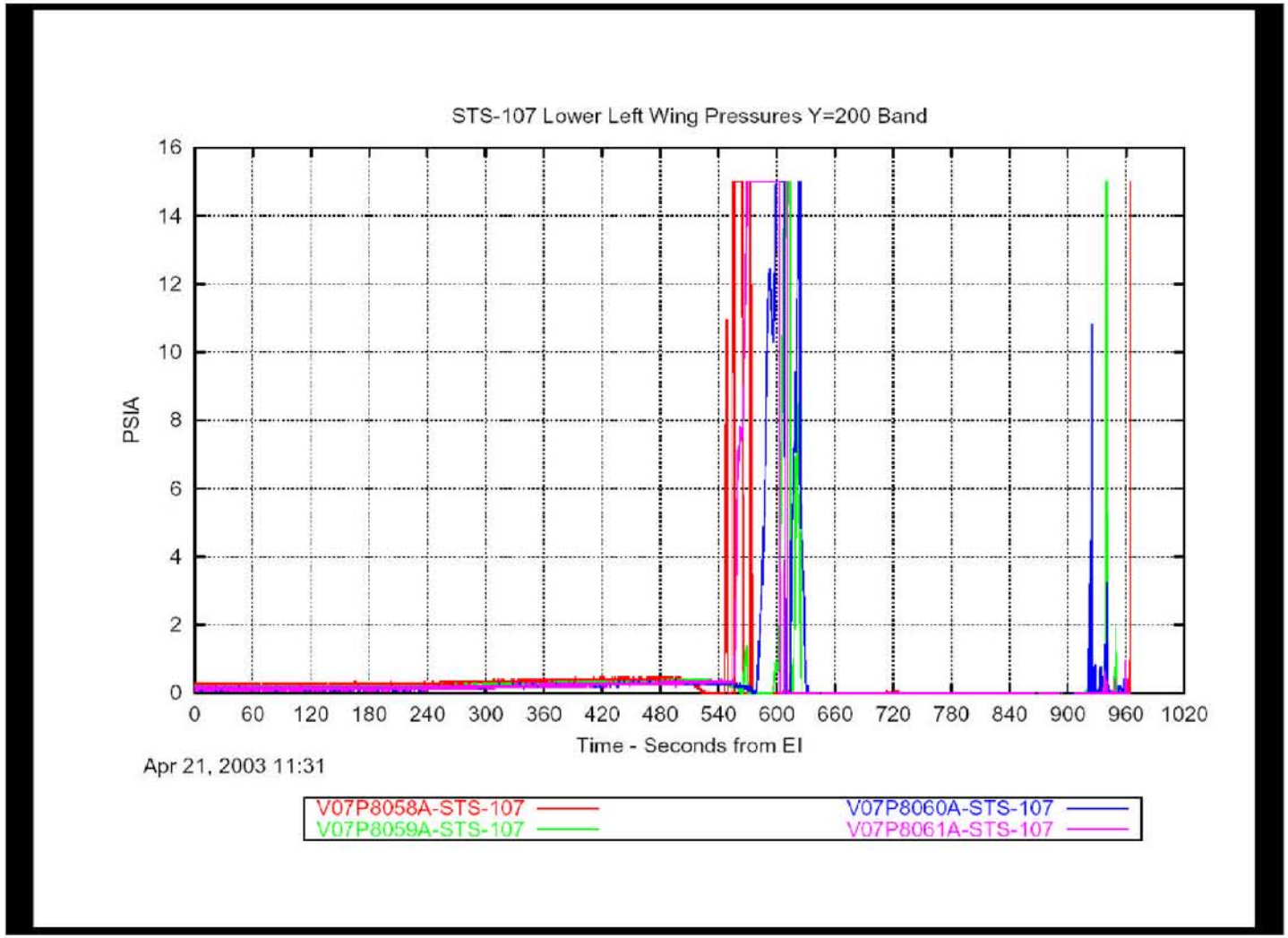
Lower Left Wing Y=150 Taps (Fwd 4)



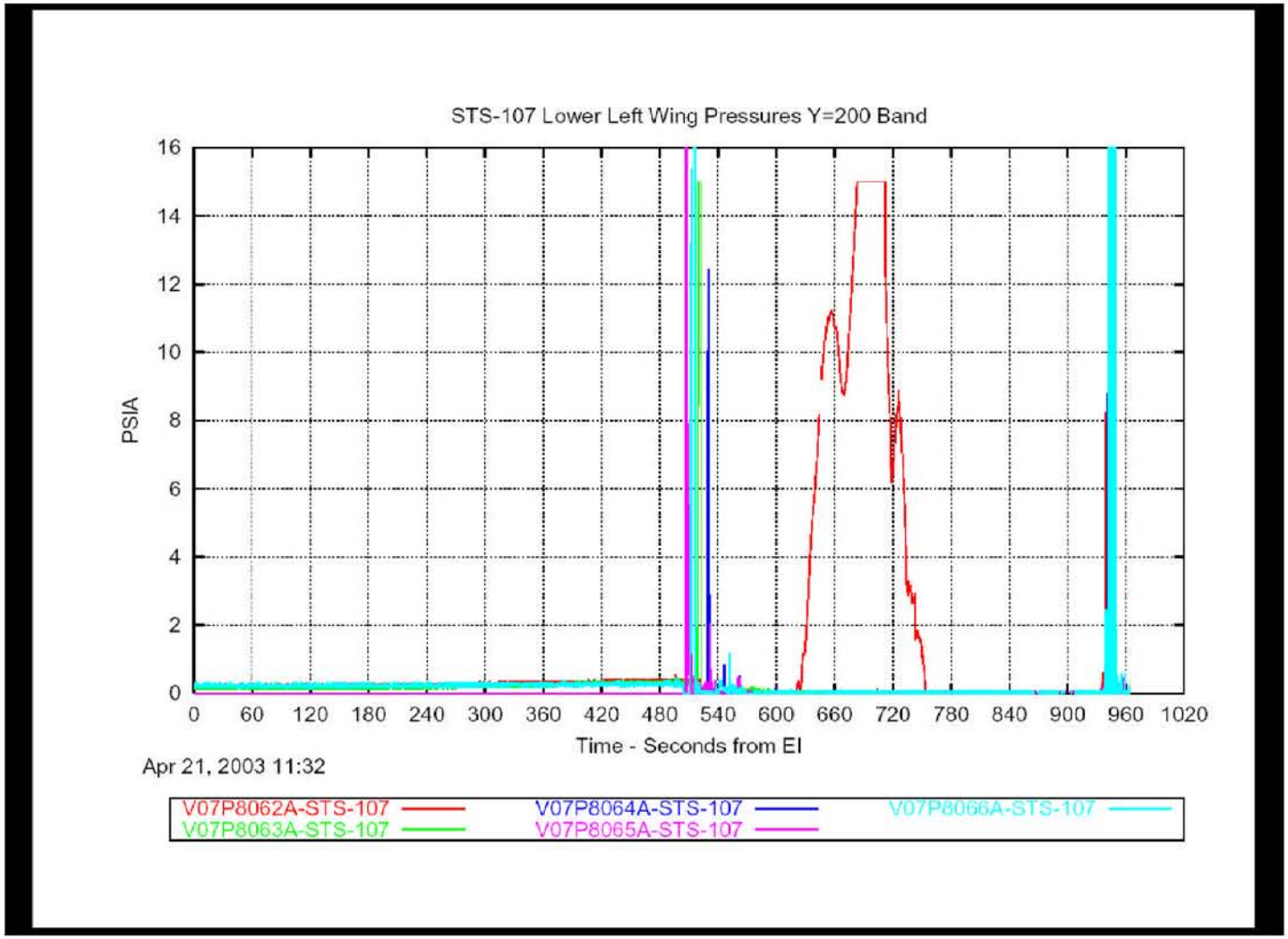
Lower Left Wing Y=150 Taps (Aft 5)



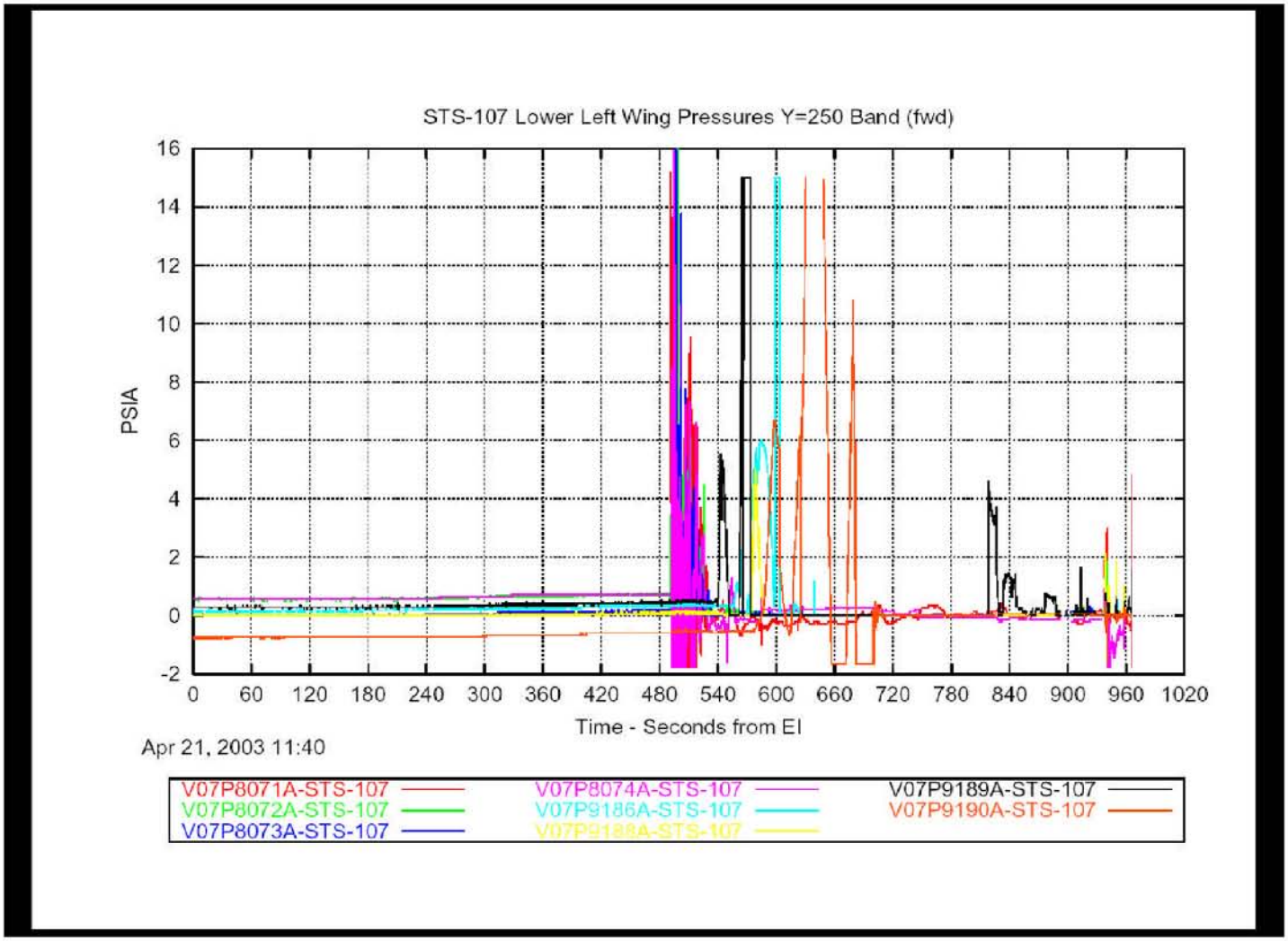
Lower Left Wing Y=200 Taps (Fwd 4)



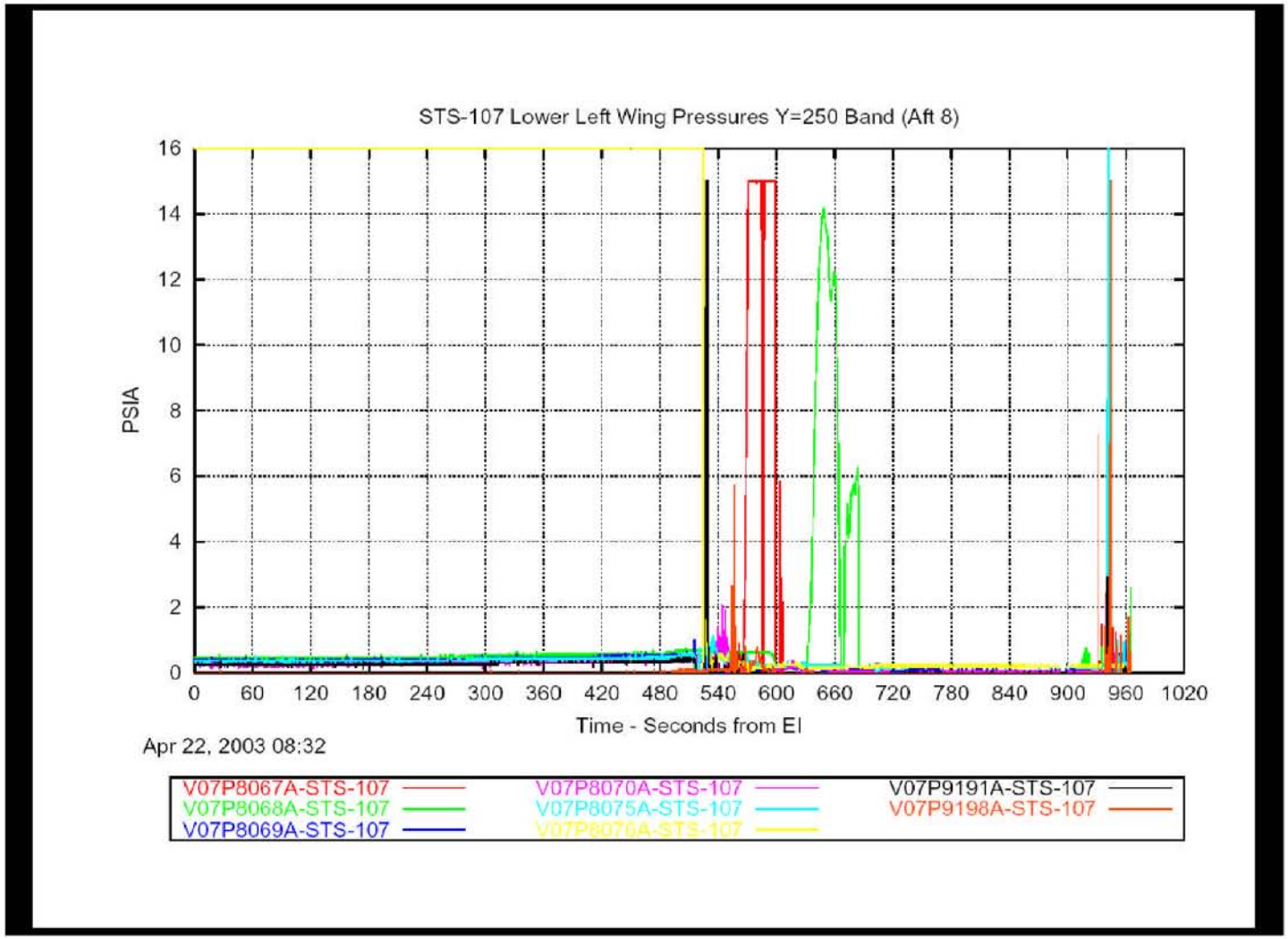
Lower Left Wing Y=200 Taps (Aft 5)



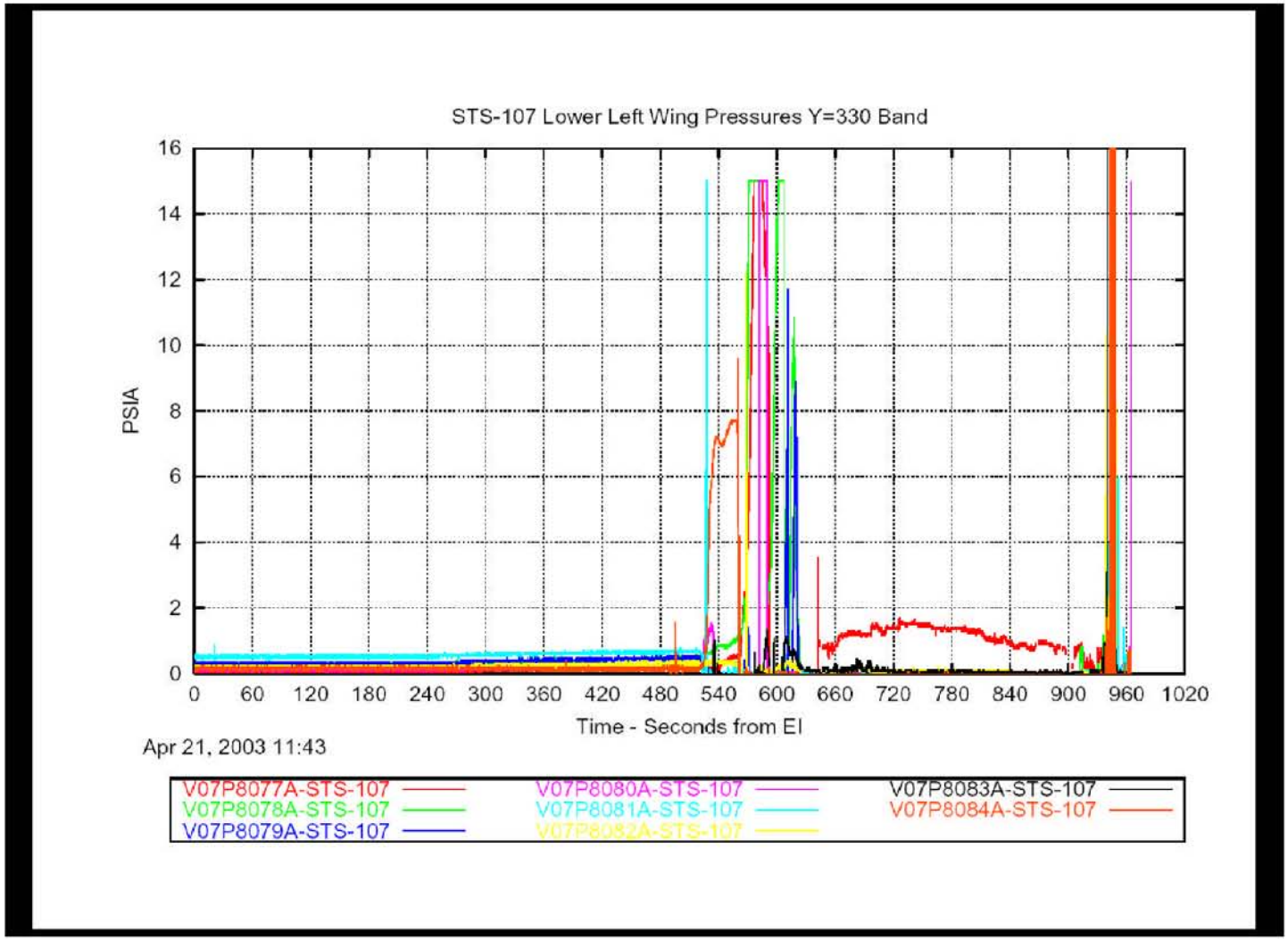
Lower Left Wing Y=250 Taps (Fwd 8)



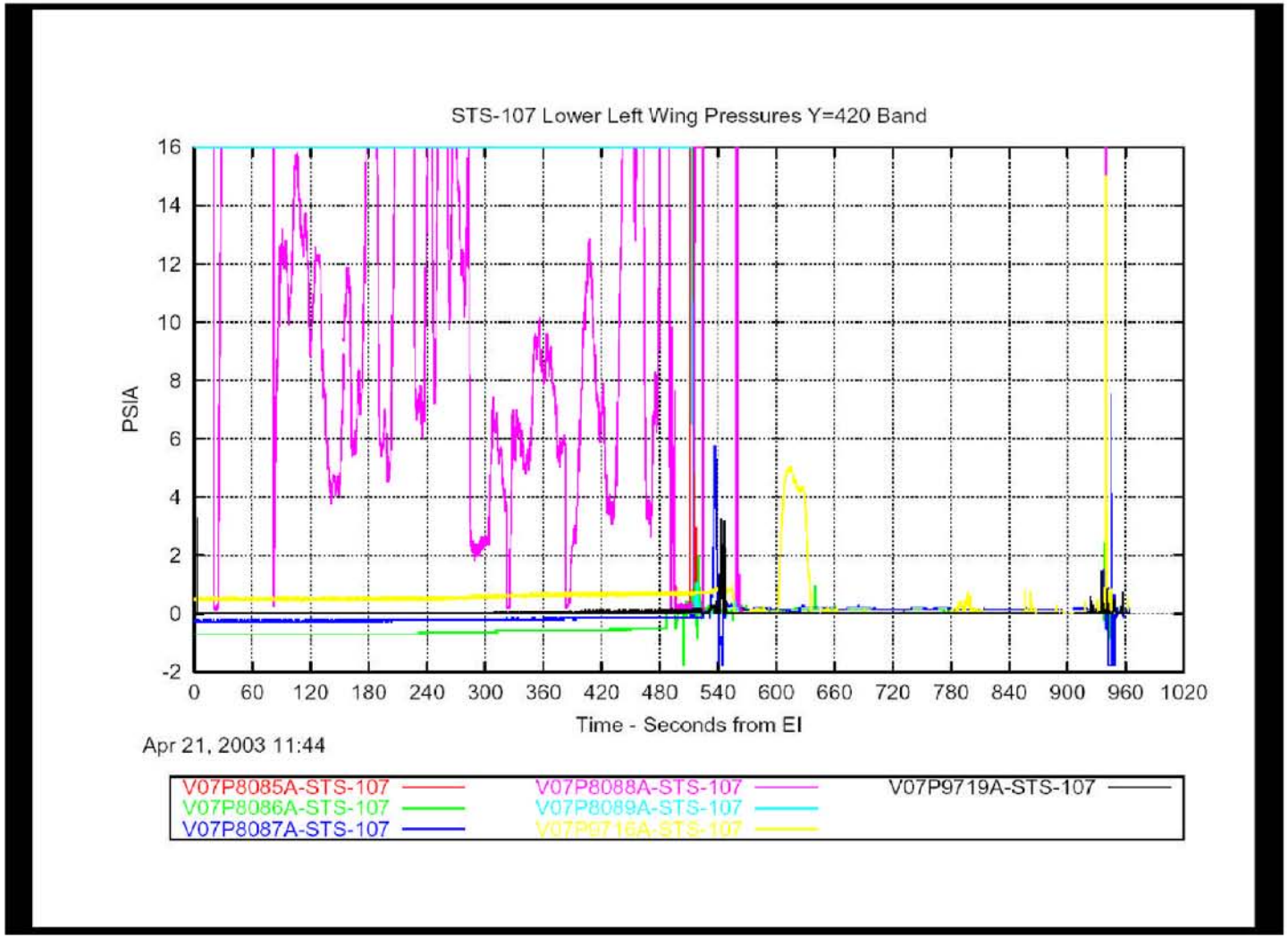
Lower Left Wing Y=250 Taps (Aft 8)



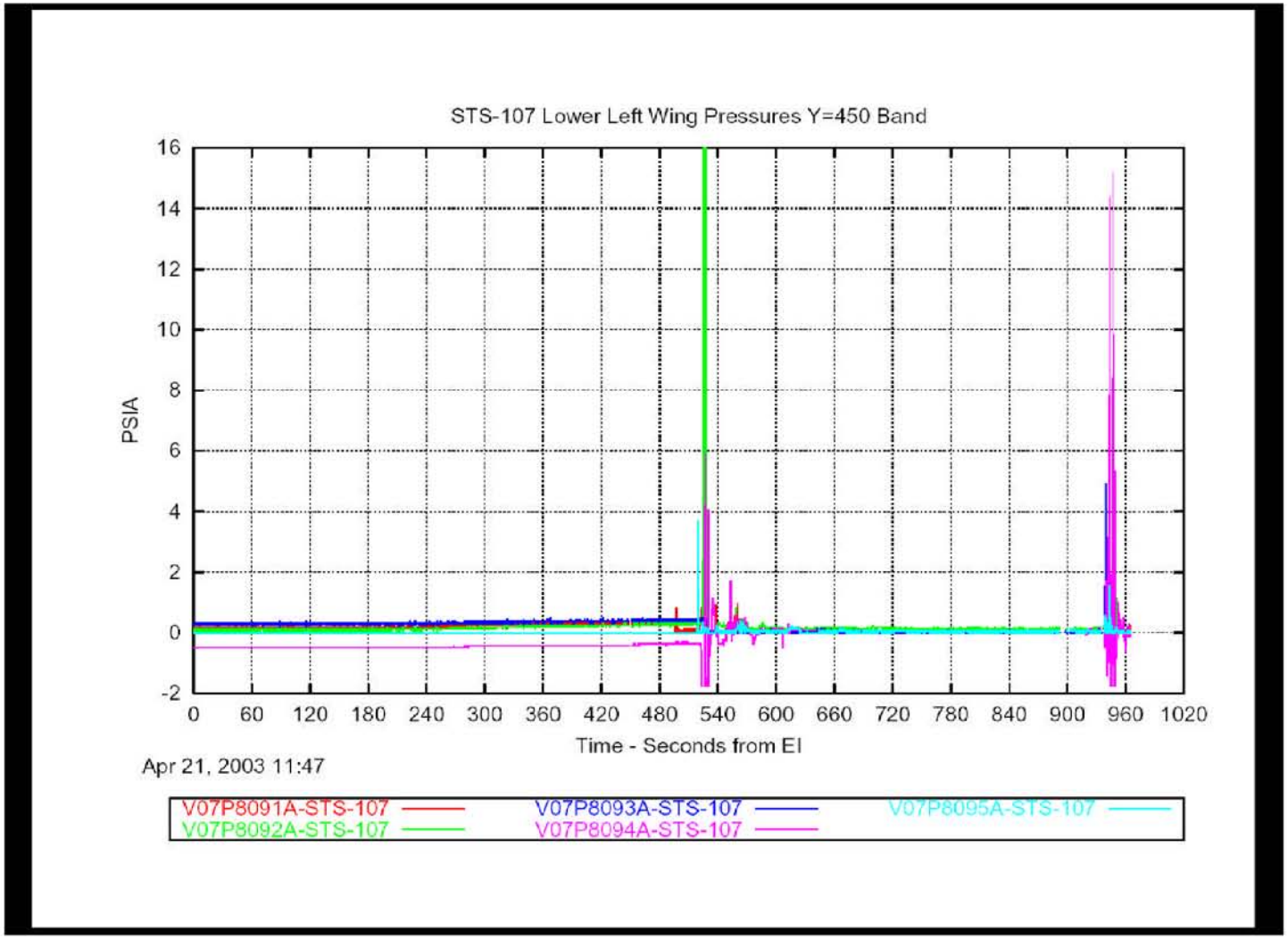
Lower Left Wing Y=330 Taps



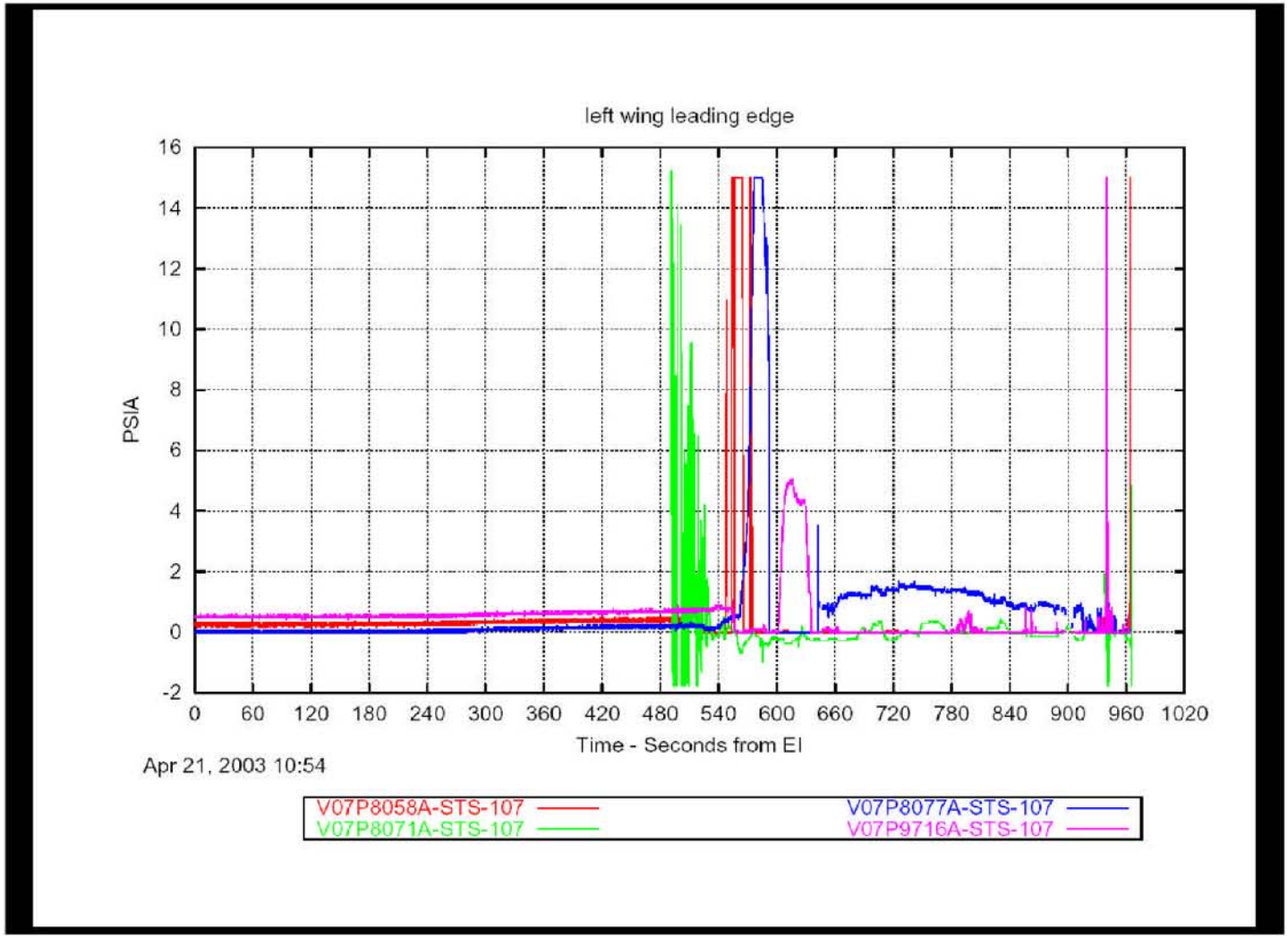
Lower Left Wing Y=420 Taps



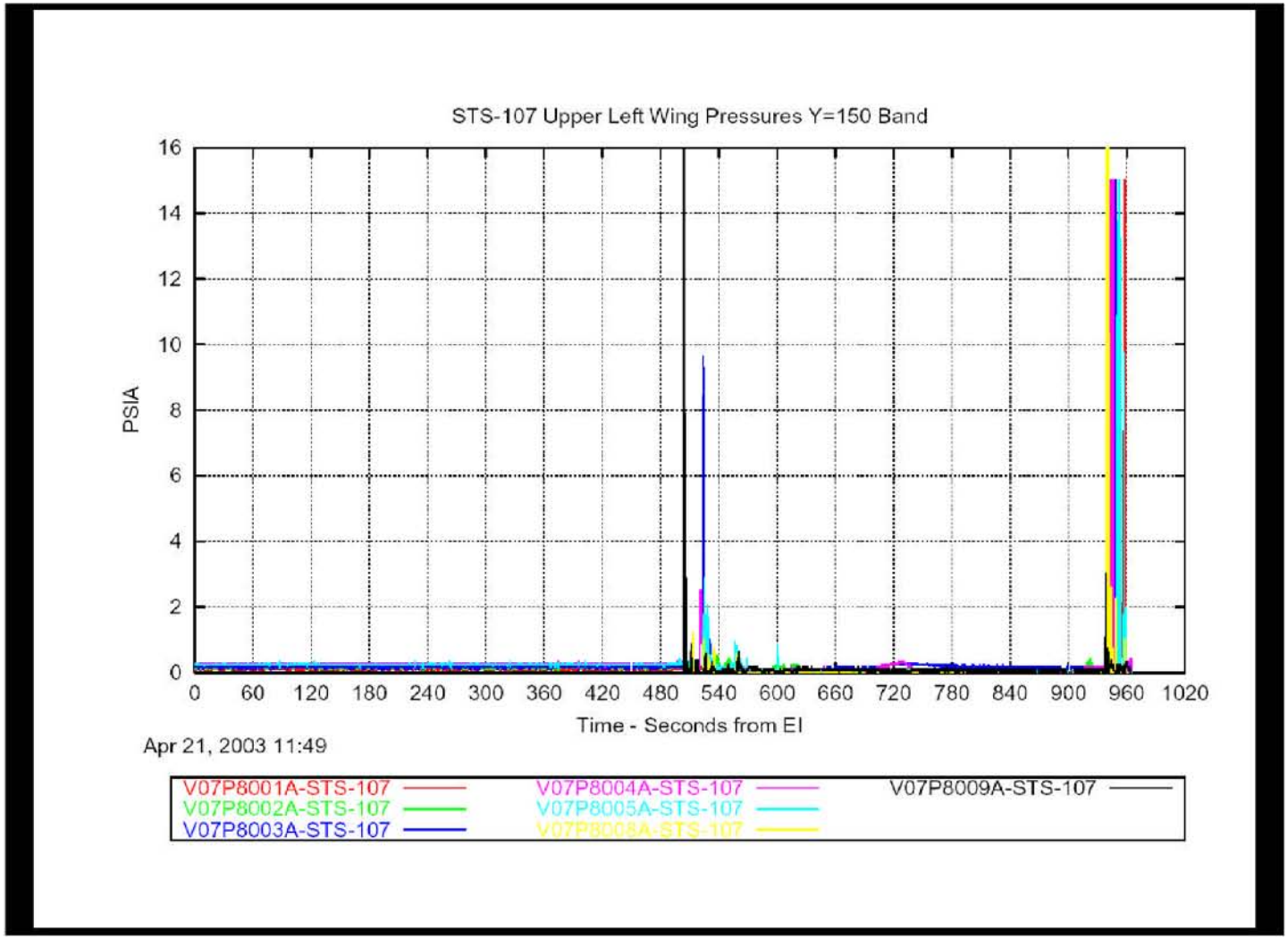
Lower Left Wing Y=450 Taps



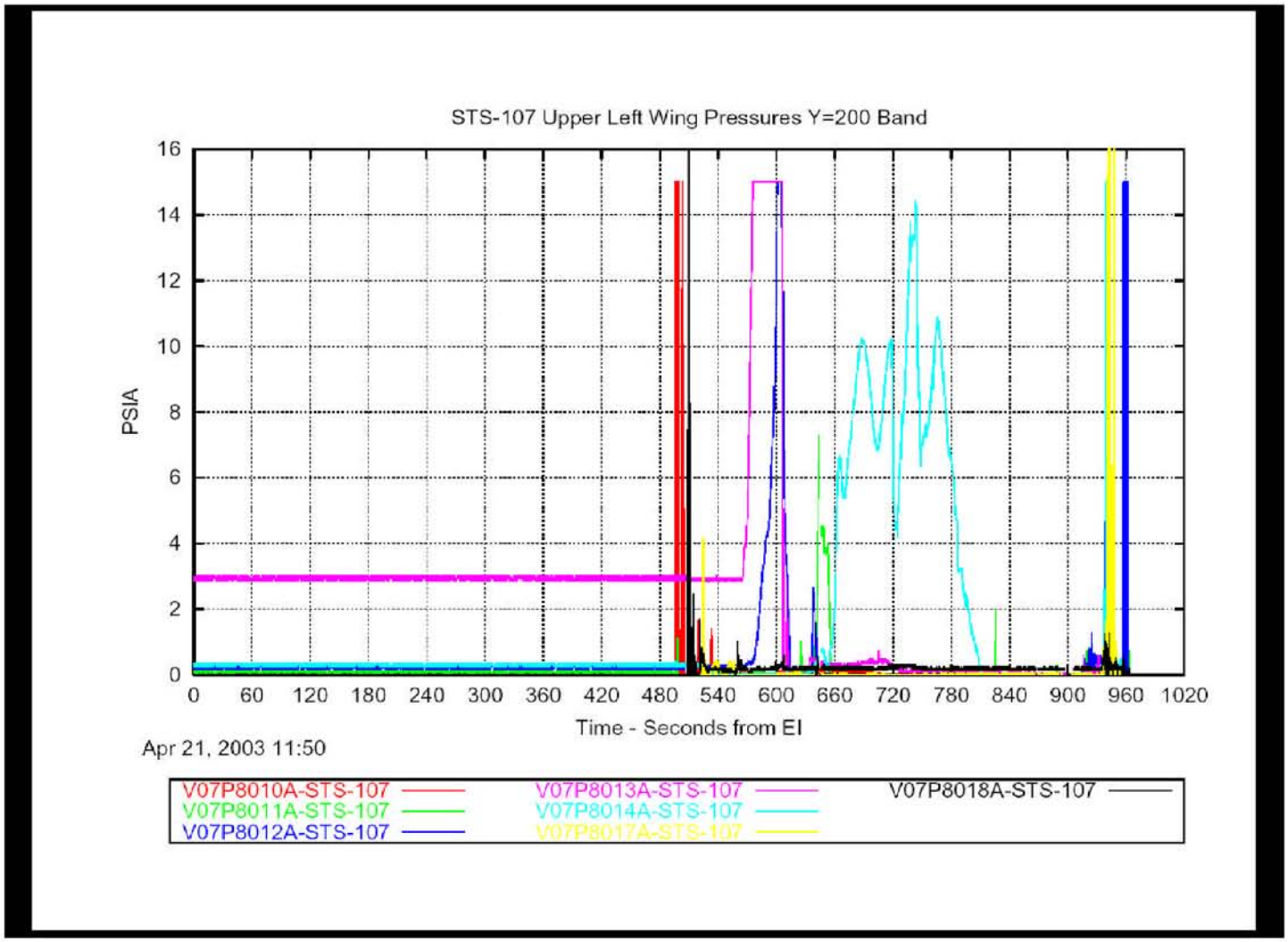
Left Wing Leading Edge (Lower) Taps



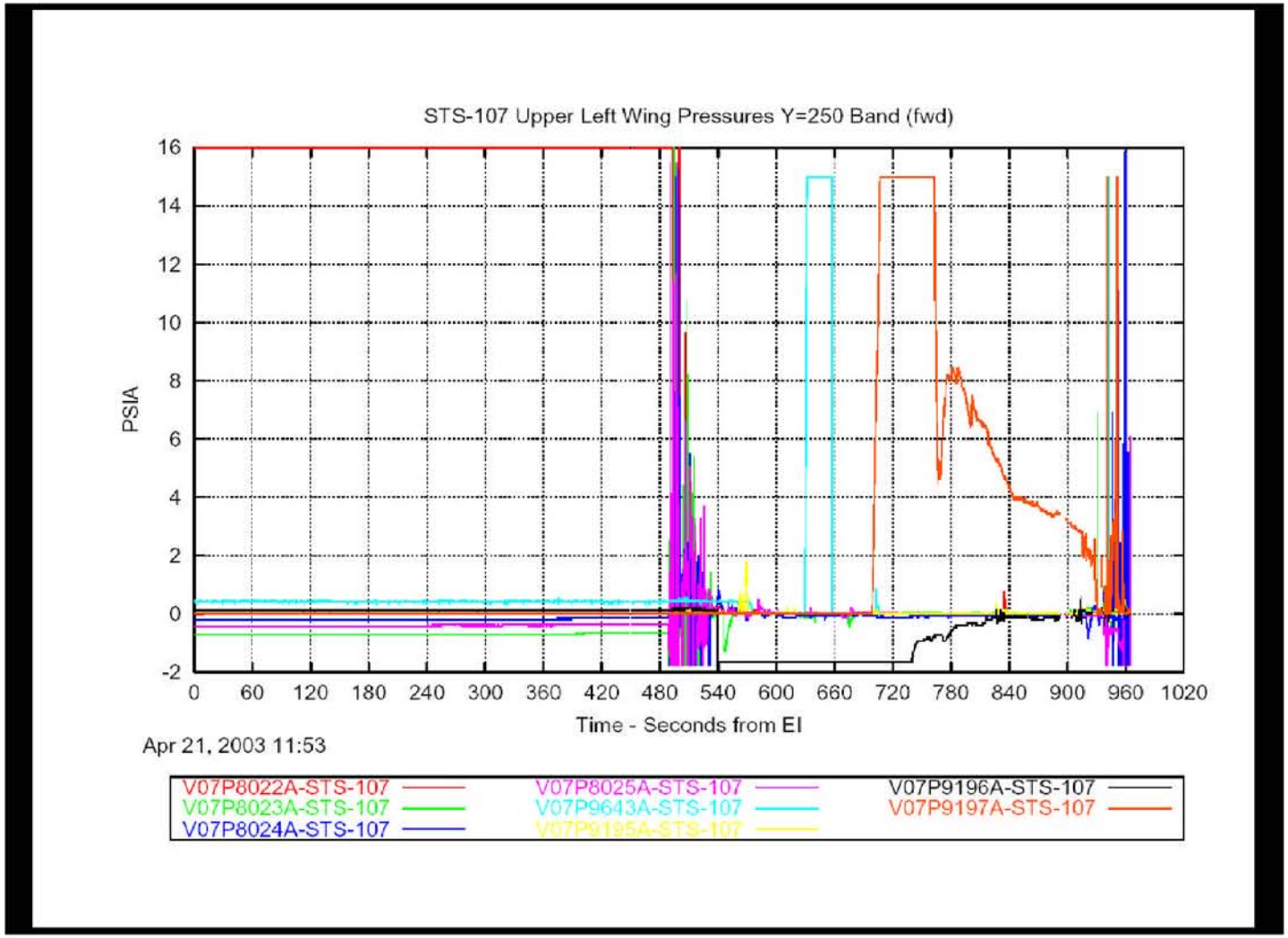
Upper Left Wing Y=150 Taps



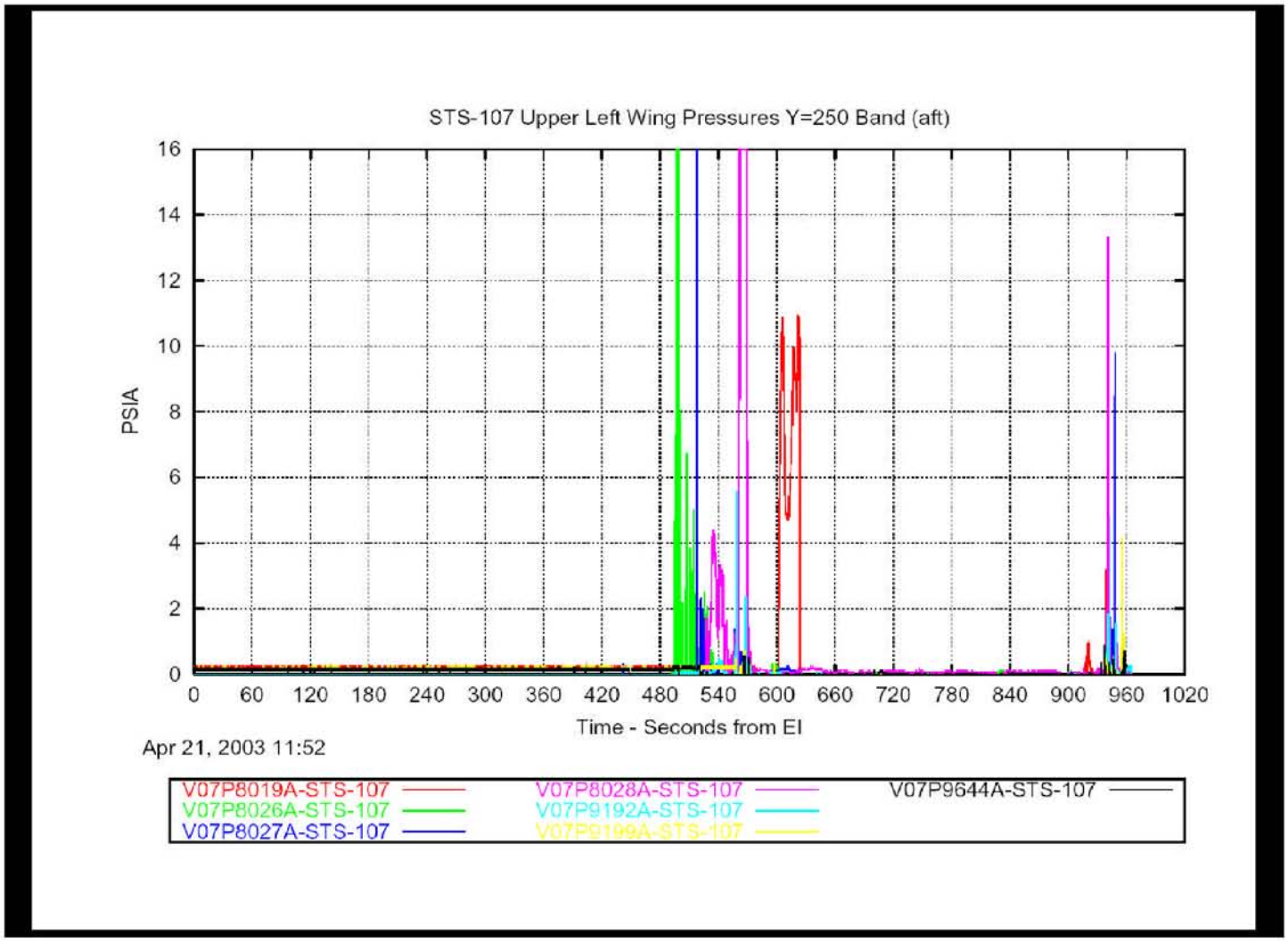
Upper Left Wing Y=200 Taps



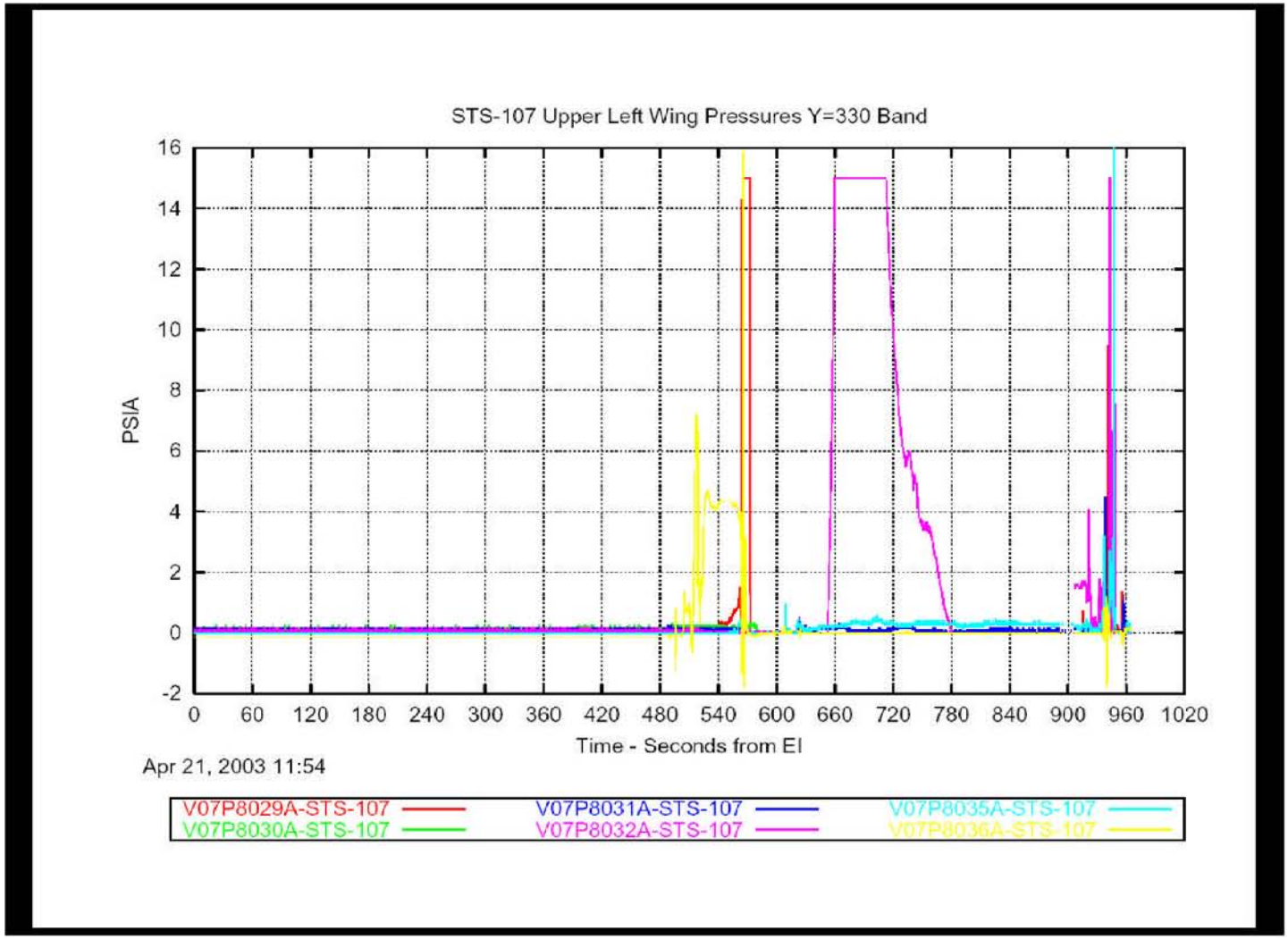
Upper Left Wing Y=250 (Fwd 8)



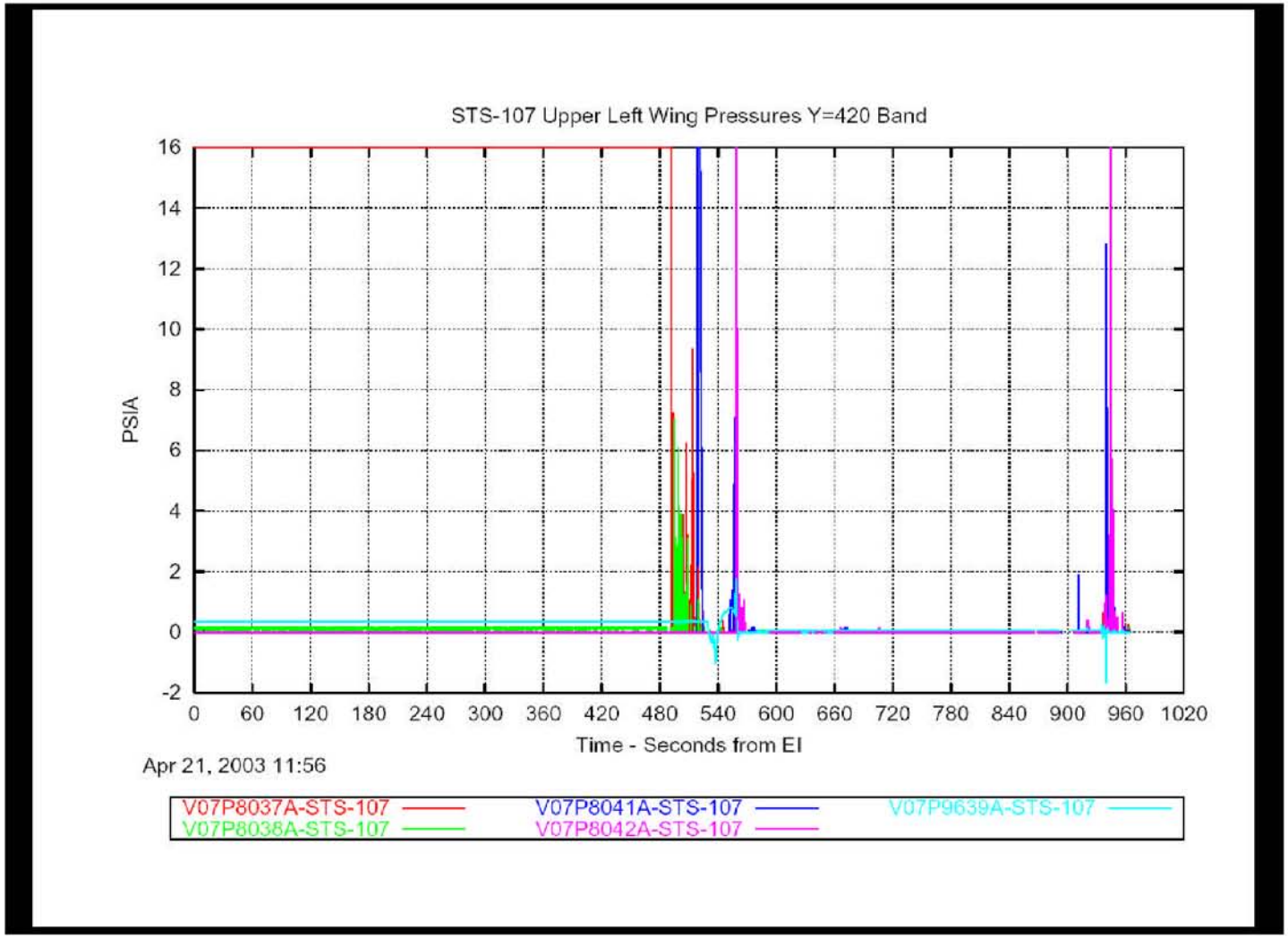
Upper Left Wing Y=250 (Aft 7)



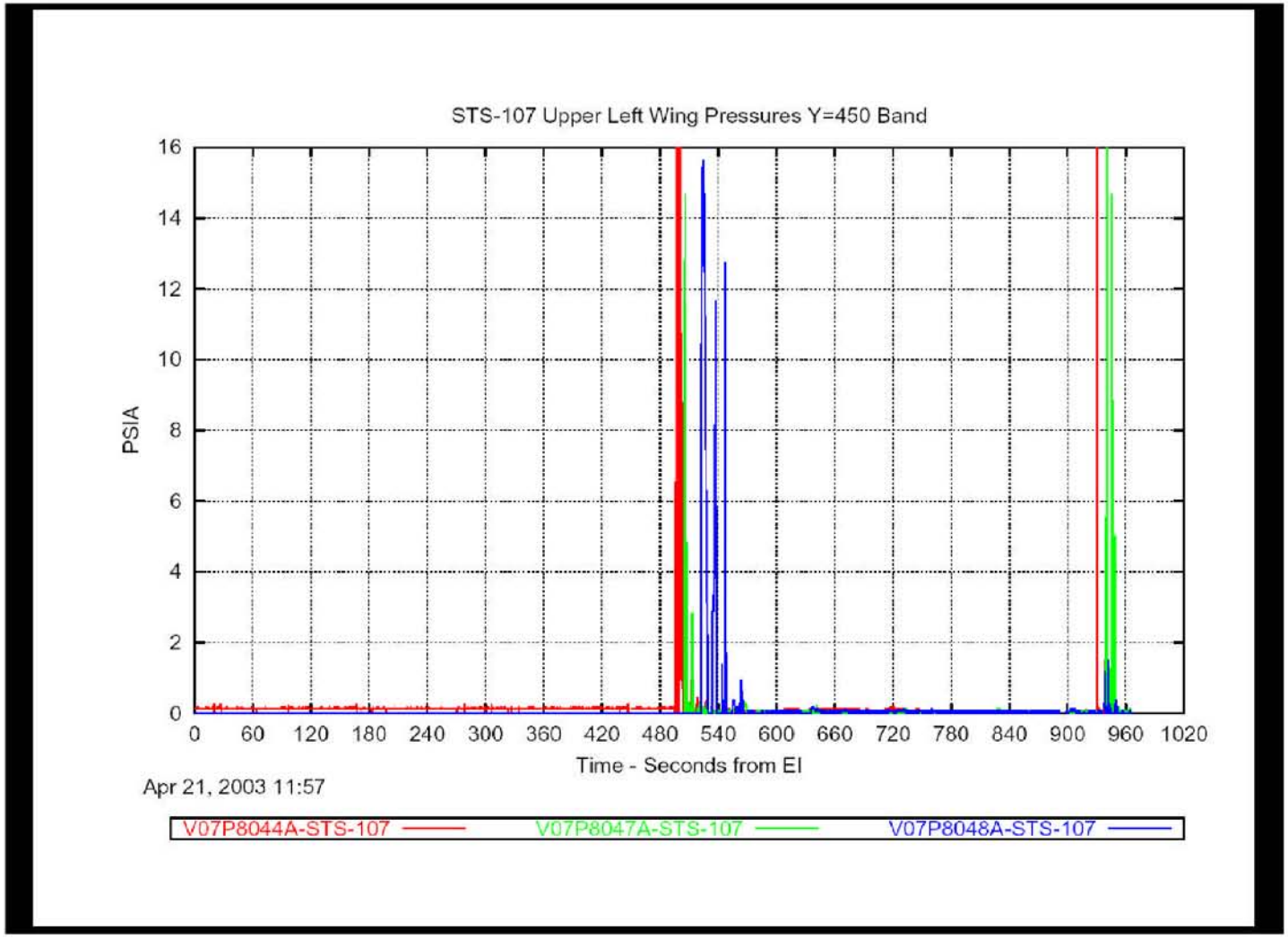
Upper Left Wing Y=330



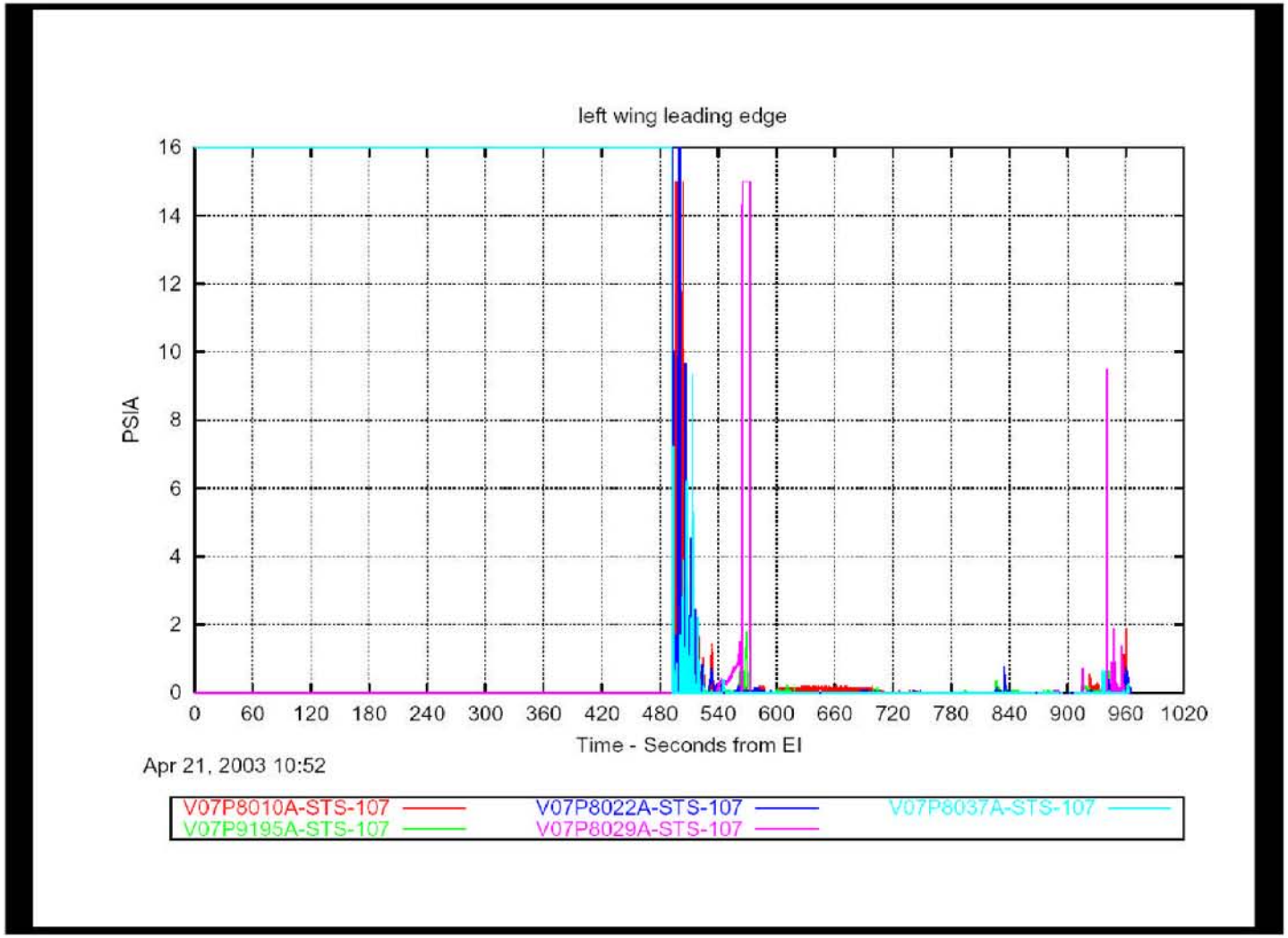
Upper Left Wing Y=420



Upper Left Wing Y=450



Left Wing Leading Edge (Upper) Taps



STS-107 x1040 Spar Cap Strain Gage Assessment

S.C. Sorenson

Boeing Houston Orbiter Stress Analysis

13 June 2003

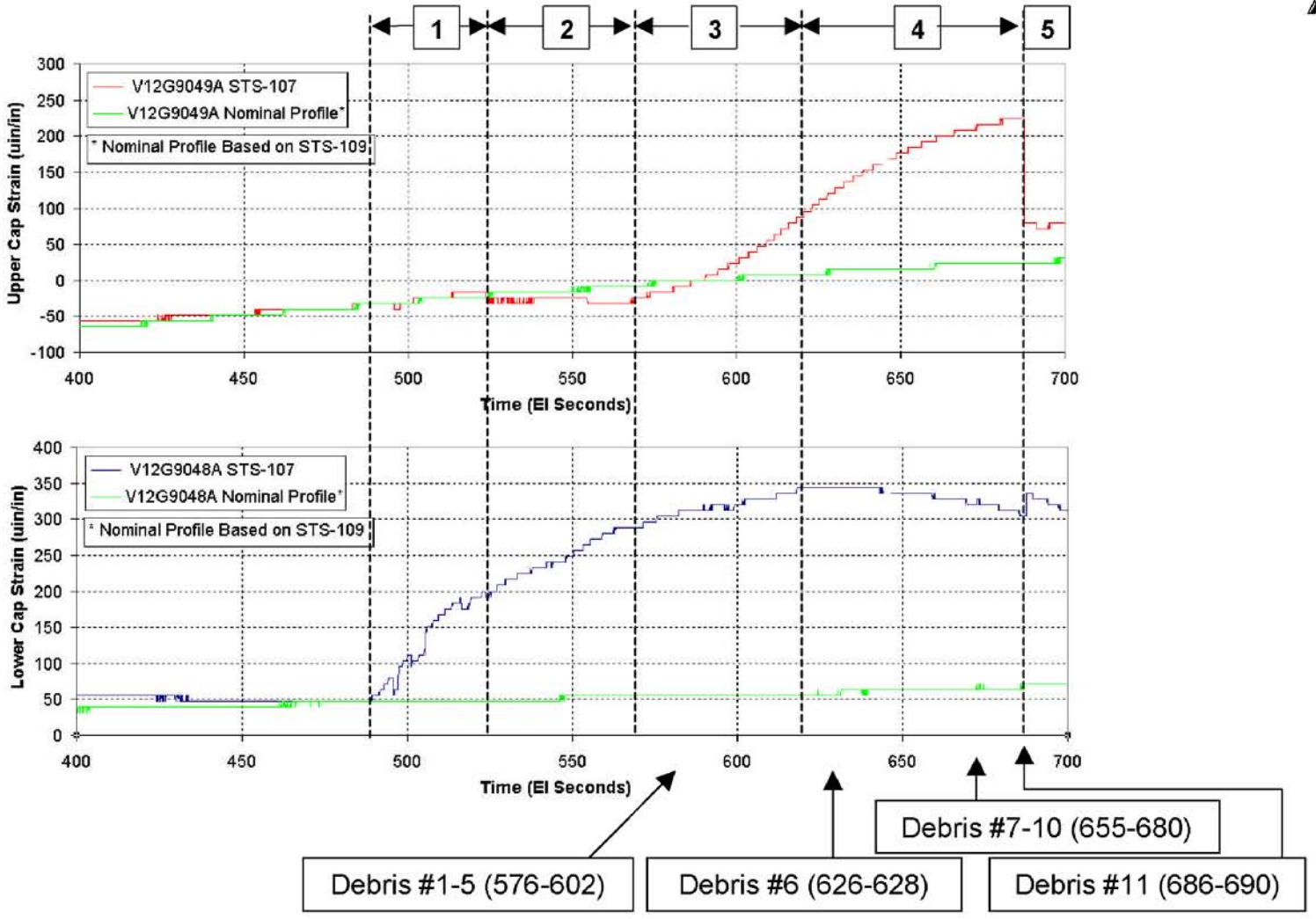
Background

- **Anomalous strain gage signatures are presumed to result from instrumentation malfunction, thermally induced strain, load redistribution, or a combination.**
  - Thermal effects are a more reasonable explanation than load redistribution scenarios.
    - Lower spar cap shows a slope sign reversal.
    - No slope changes before or after sharp data changes.
- **The current analysis uses FEM methods to assess the feasibility of thermally induced strain as a mechanism to produce the observed signatures.**
  - Analysis does not attempt to model actual structural temperatures.
    - Objective is to determine the structural response to local temperature differentials.

STS-107 Data Examination

- **STS-107 upper and lower spar cap strain data was examined and refined for analysis.**
  - Sharp data drop near EI+690 seconds is questionable data.
    - Drop occurs in one time step
      - No preceding slope change.
    - Current opinion of instrumentation is that the data is good up to the terminal phase (~EI+930 sec)
    - Also extremely unlikely as a real strain event
    - Data beyond EI+690 seconds will not be analyzed.
  - Nominal trend lines, based on STS-109 entry data, were superimposed for comparison.
- **Key data event times were annotated.**

STS-107 Reconstructed Data



FEM Results Summary

Qualitative summary of analyzed FEM cases & results:

Case	Description	Upper Cap Reaction	Lower Cap Reaction
4A	Calibration (all nodes @ 70°F)	None	None
4B	Equal heating of spar web, forward upper and lower skins	Significant tension (20% higher than lower cap)	Significant tension
4C	Heating of outboard, aft, upper skin only	Significant tension	Very low tension
4D	Combined 4B and 4C	Significant tension (effects additive)	Significant tension (effects additive)
4F	Heating forward lower skin only	Very low compression	Significant tension
4G	Heating of WLE nodes	Very low compression	Low compression (2x upper cap)
4H	Heating of outboard, aft, lower skin only	Very low compression	Very low tension
4I	Heating of spar web nodes only	Very low tension	Low tension (2x upper cap)
4J	Heating of Yo167 rib sections	Very low tension	Very low tension
4L	Heating of upper spar cap only	Significant compression	Very low compression
4M	Heating of aft upper skin only	Significant tension	Very low compression

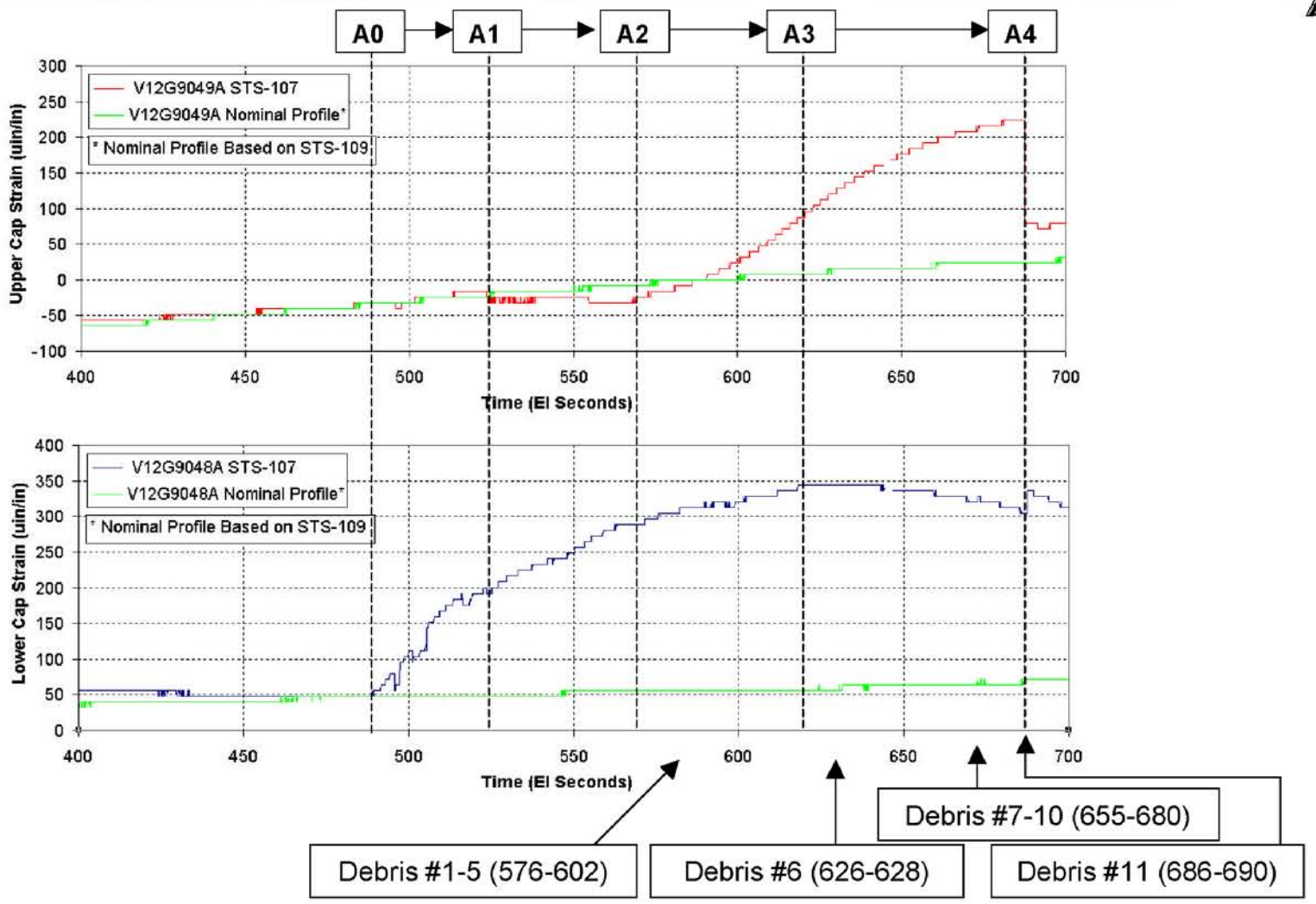
FEM Results Analysis

- **FEM temperature load cases may be combined in a number of ways to generate temperature profile sequences which produce the observed strains.**
  - Several profile sequences were developed, and screened versus corroborating scenario evidence to define the most likely profile that could have produced the observed strains.
- **The most rational temperature profile was selected.**
  - Combined heating of aft upper skin, spar web, upper and lower forward skins, and upper spar cap, with less heating to lower spar cap.

FEM Scenario Temperature Profile

Case	Description	Upper Cap Reaction	Lower Cap Reaction	Scenario
A1	+40°F applied to spar web, forward upper & lower skins, and upper spar cap +75°F applied to outboard, aft, upper skin	13 µin/in **(8 µin/in) (Recorded strain)**	146 µin/in **(152)**	Heating in front of spar and aft upper skin.
A2	+75°F applied to spar web, forward upper & lower skins, and upper spar cap +120°F applied to aft, upper skin along y167 rib +5°F applied to lower spar cap	-11 µin/in **(-16)**	225 µin/in **(232)**	Continued heating in front of spar and aft upper skin. Some heating in lower spar cap.
A3	+105°F applied to spar web, forward upper & lower skins, and upper spar cap +145°F applied to aft, upper skin above MLG wheel well +10°F applied to lower spar cap	73 µin/in **(72)**	291 µin/in **(288)**	Continued heating in front of spar and aft upper skin. Continued heating in lower spar cap.
A4	+105°F applied to spar web, forward upper & lower skins, and upper spar cap +190°F applied to aft, upper skin above MLG wheel well +20°F applied to lower spar cap	200 µin/in **(200)**	237 µin/in **(232)**	Thermal EQ in spar web, forward skins, and upper cap. Continued heating in lower cap. Continued heating of aft upper skin.

FEM Scenario Timeline Plot



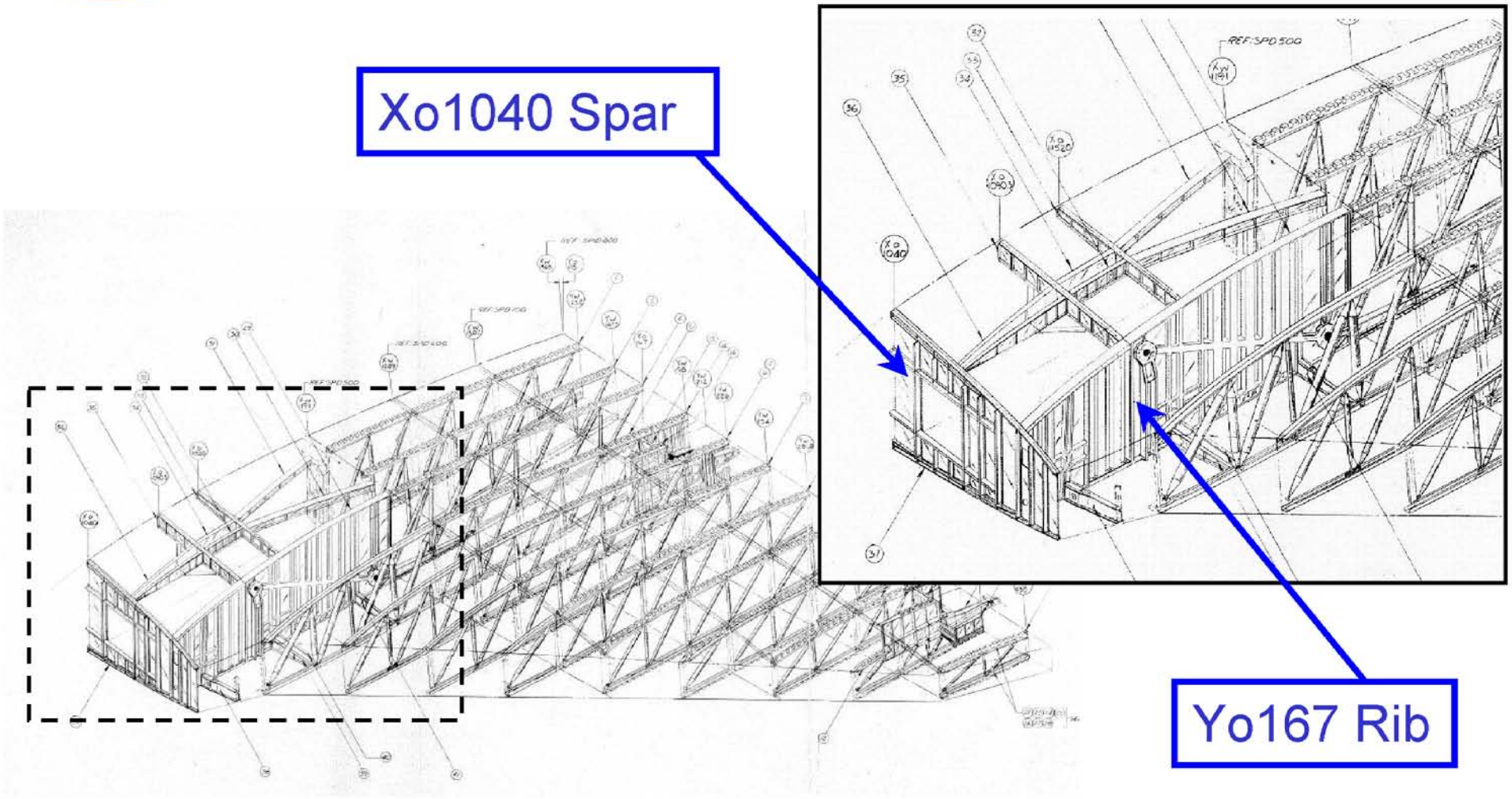
Conclusions

- **Local temperature gradients could potentially explain the observed Xo1040 upper and lower spar cap strains.**
- **Strain gage evidence offers some support for failure scenarios involving hot gas intrusion from the wing cavity into the glove area and/or the MLG wheel well.**
  - Timing of strain gage events has reasonable correlation with breach times of WLE and MLG well.
- **Strain gage data does not, however, conclusively indicate this scenario.**
  - Results require the critical assumption that the lower spar cap is initially exposed to less heating than the upper cap, spar web, and nearby skins.

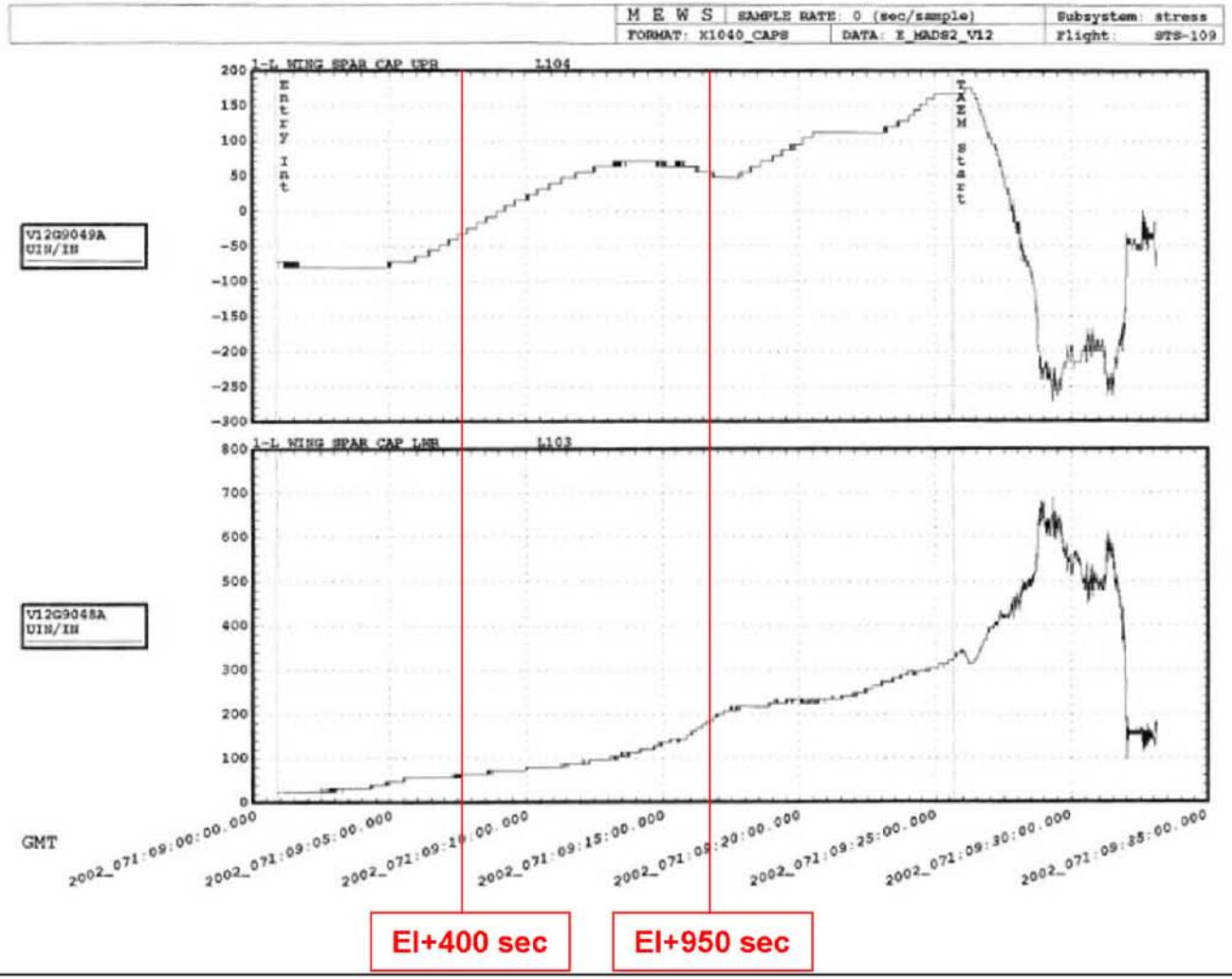
Backup

- Wing Illustration
- Nominal entry strain plots
- STS-107 Full Data Reconstruction
- FEM Illustrations
- FEM Case Results Summary

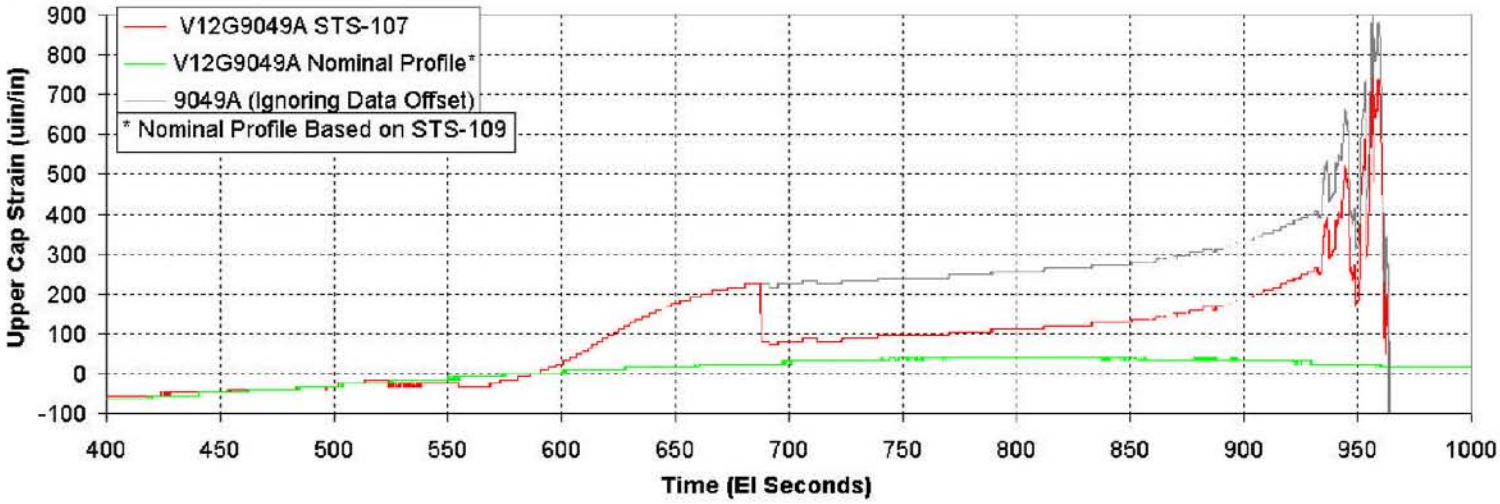
Wing Illustration

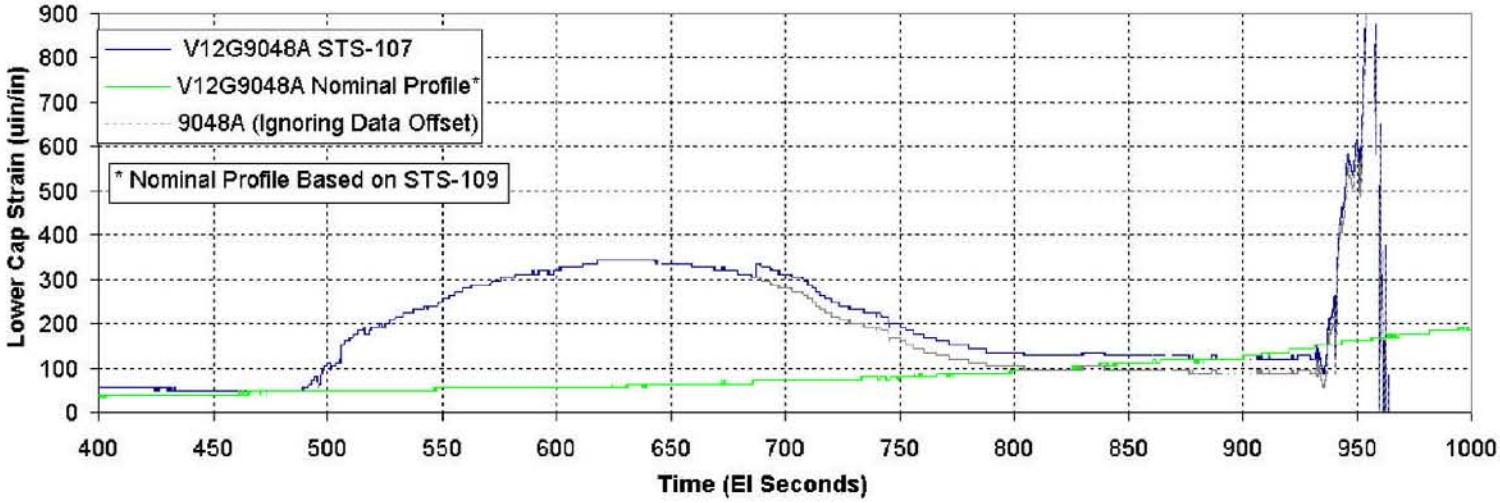


Nominal Entry Strain Plots (STS-109)

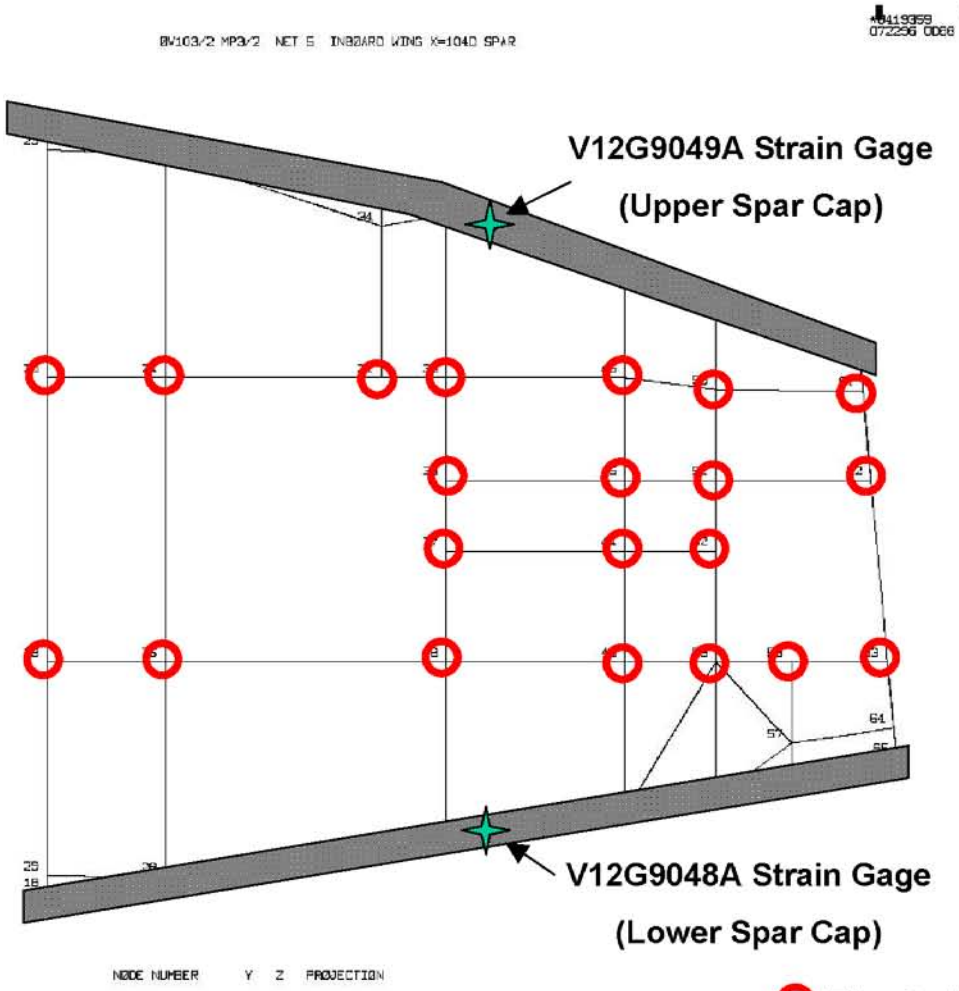


STS-107 Full Data Reconstruction



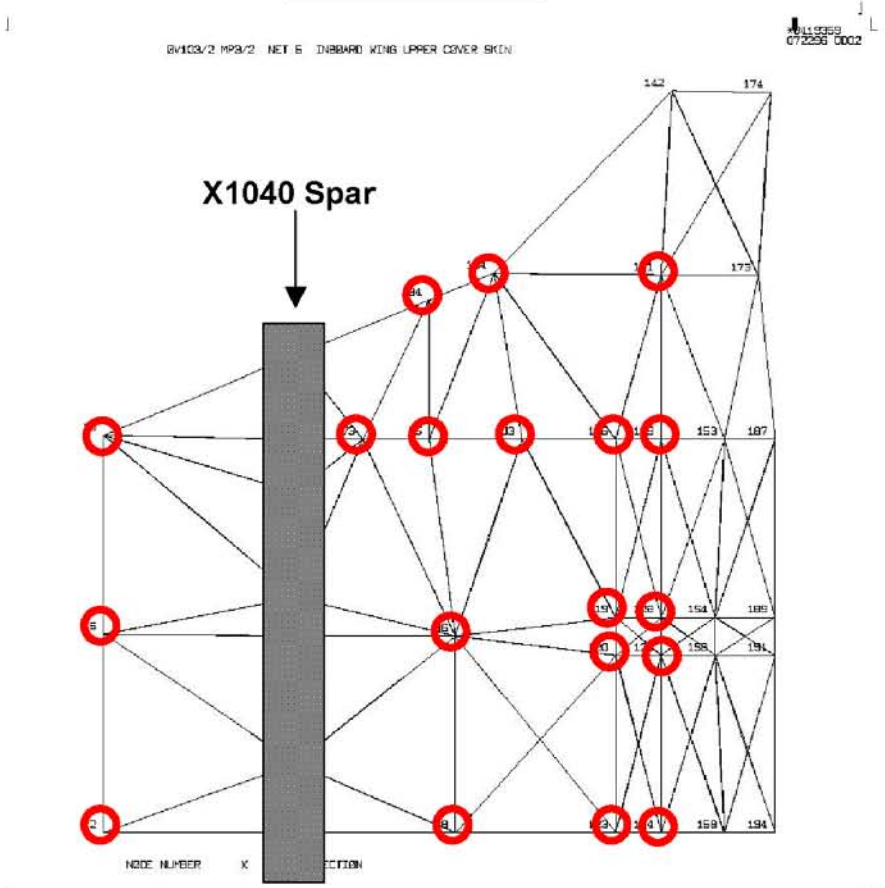


FEM Illustration – x1040 Spar Nodes

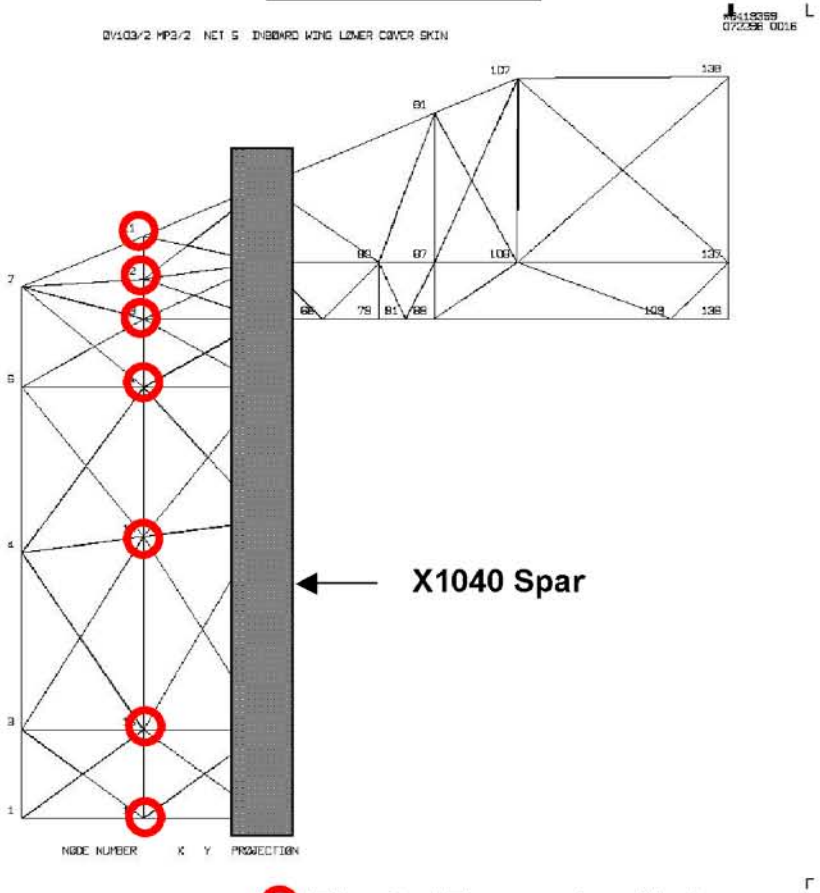


FEM Illustration – Nearby Skin Nodes

UPPER SKIN



LOWER SKIN



Elevated Temperature Node

FEM Case Results Summary

Case	Description	Temperatures: Default	Spar Web	Upper Skin	Lower Skin	Upper Spar Cap	Lower Spar Cap	Obd/Aft Upper Skin	Other (see notes)		Results: Stress	Microstrain	Notes
4A	Calibration Case	70	70	70	70	70	70	70	-	Upper Cap (5073)	0	0	
										Lower Cap (5090)	0	0	
4B	Equal heating of spar web, upper and lower skins	70	180	180	180	70	70	70	-	Upper Cap (5073)	3749	354	
										Lower Cap (5090)	4445	419	
4C	Heating of only outboard, aft upper skin	70	70	70	70	70	70	400	-	Upper Cap (5073)	6668	629	
										Lower Cap (5090)	451	43	Nodes 73, 84, 95, 104, 103, 116, 141, 129
4D	Heat spar web, upper & lower skins, and outboard aft upper skin	70	180	180	180	70	70	400	-	Upper Cap (5073)	10416	983	
										Lower Cap (5090)	4896	462	
4F	Heat lower skin near spar only	70	70	70	180	70	70	70	-	Upper Cap (5073)	-171	-16	
										Lower Cap (5090)	2210	208	
4G	Heat WLE nodes near panels 8/9	70	70	70	70	70	70	70	400	Upper Cap (5073)	-276	-26	
										Lower Cap (5090)	-602	-57	Nodes at y226 to 400°F
4H	Heating of only outboard, aft lower skin	70	70	70	70	70	70	70	400	Upper Cap (5073)	-377	-36	
										Lower Cap (5090)	119	11	Outboard, aft lower skin
4I	Heat spar web nodes only	70	110	70	70	70	70	70	-	Upper Cap (5073)	413	39	
										Lower Cap (5090)	863	81	Compare to 4E
4J	Heat sections of y167 Rib	70	70	70	70	70	70	70	200	Upper Cap (5073)	1	0	
										Lower Cap (5090)	5	0	167 Rib Web Nodes to 200°F
4K	Heating of only outboard, aft upper skin (see 4C)	70	70	70	70	70	70	200	-	Upper Cap (5073)	2627	248	
										Lower Cap (5090)	178	17	Compare to 4C
4L	Heating of only upper spar cap nodes	70	70	70	70	150	70	70	-	Upper Cap (5073)	-5474	-516	
										Lower Cap (5090)	-343	-32	
4N	Heating of only aft upper skin (wheel well)	70	70	70	70	70	70	70	200	Upper Cap (5073)	3951	373	
										Lower Cap (5090)	-184	-17	4M plus nodes 73,95,103,116,129
M1	Mechanical load case TABR 2130 No Damage	-	-	-	-	-	-	-	-	Upper Cap (5073)	-1472	-139	
										Lower Cap (5090)	5868	554	
M2	Mechanical load case TABR 2130 Removed outboard aft upper skin	-	-	-	-	-	-	-	-	Upper Cap (5073)	-1432	-135	
										Lower Cap (5090)	5802	547	
A1	Combined heating	70	110	110	110	110	70	145	-	Upper Cap (5073)	141	13	
										Lower Cap (5090)	1549	146	
A2	Combined heating II	70	145	145	145	145	75	-	190	Upper Cap (5073)	-116	-11	Lose outboard aft upper skin (set to 70)
										Lower Cap (5090)	2388	225	Heat nodes 73,95,103,116,129 only
A3	Combined heating III	70	175	175	175	175	80	-	215	Upper Cap (5073)	777	73	
										Lower Cap (5090)	3082	291	Heat aft upper skin (wheel well) to 215
A4	Combined heating IV	70	175	175	175	175	90	-	260	Upper Cap (5073)	2122	200	
										Lower Cap (5090)	2513	237	Heat aft upper skin (wheel well) to 260

Induced Thermal Strain Scenario

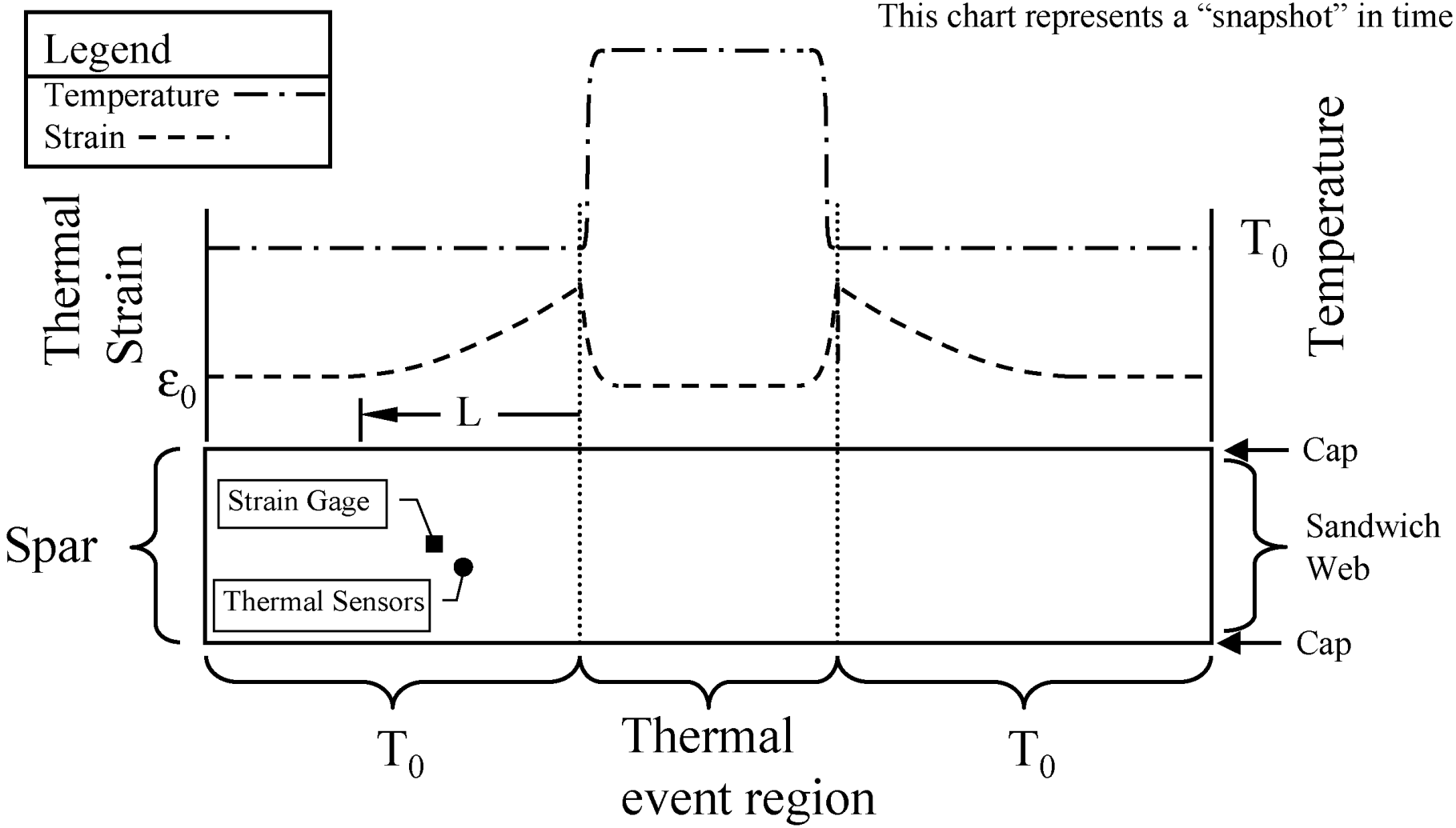
Presented by: Paul Parker

What is strain reaction both near and far from thermal event?

- How does strain react to distant thermal event?
- Thermal event occurs locally in structure
  - Maximum strain at thermal event boundary
  - Far field strains induced by thermal event
    - How far away, L, from thermal event does thermally induced strain field extend?
  - Strains reduce away from thermal event boundary
- Specifically focused on gage V12G9921A near panel 9 in middle of spar

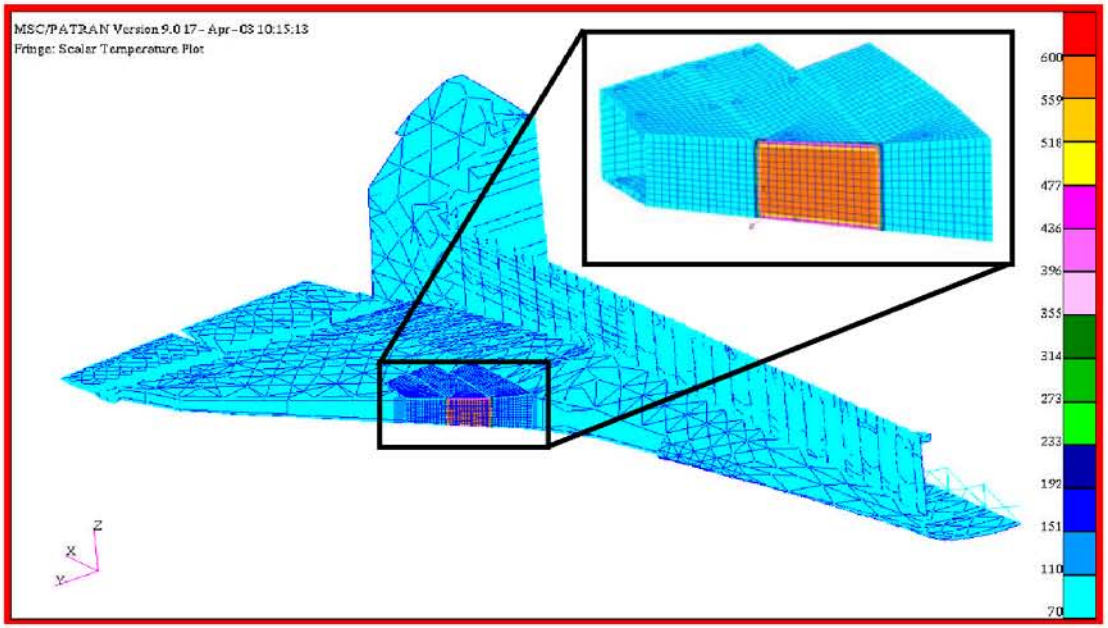
Temperature Readings Lag Strain Measurements

This chart represents a "snapshot" in time



Existing Model Refined for Local Region of Interest

- **Model Description**
  - Spar model developed from existing loads model
    - Refined mesh on loads model in local region of interest
    - Incorporated temperature dependent CTE and Young's Modulus



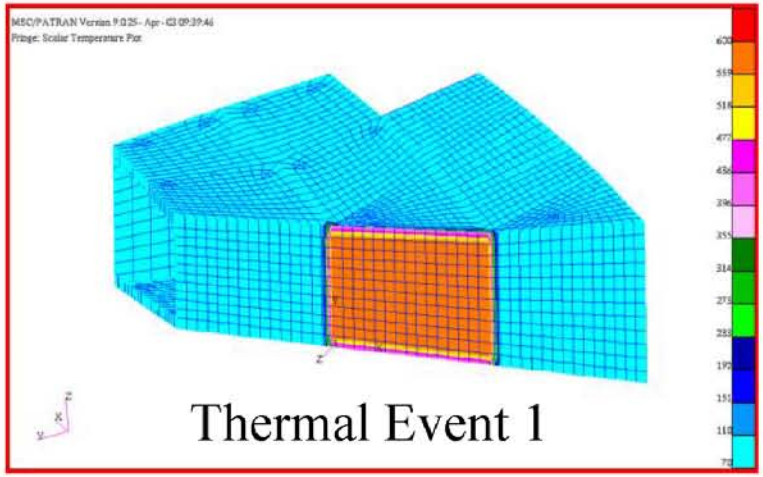
Multiple Thermal Events Analyzed

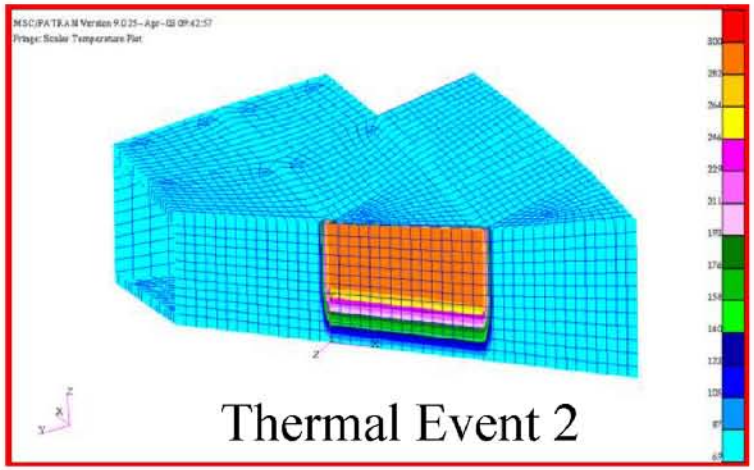
- **Five thermal events analyzed**
  1. Assumed 600°F on WLE web, 400°F on spar caps, 70°F on rest of structure
  2. Assume upper half WLE sees primary heating
     - Assumed initial heating of 300°F on upper half of WLE spar web and cap
     - Assumed linear temperature distribution of 300°F to 70°F from middle of WLE web to bottom WLE cap
     - 70°F on rest of structure
  3. Continue heating upper half WLE sees primary heating
     - Assumed 600°F on upper half of WLE spar web and cap
     - Assumed linear temperature distribution of 600°F to 70°F from middle of WLE web to bottom WLE cap
     - 70°F on rest of structure

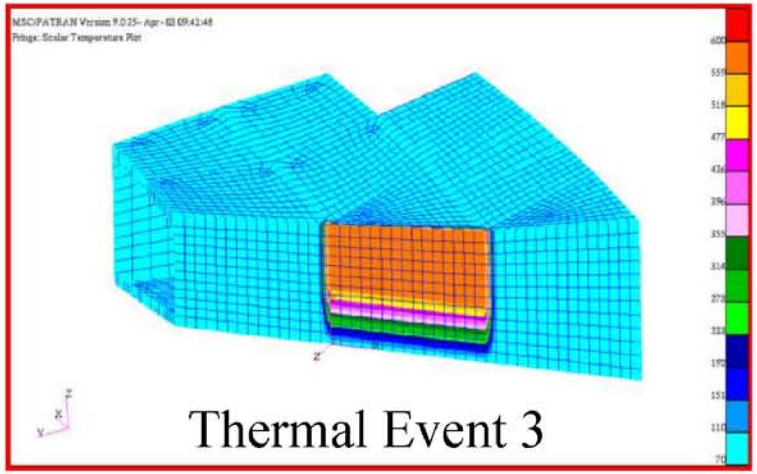
Thermal Events Analyzed Continued…

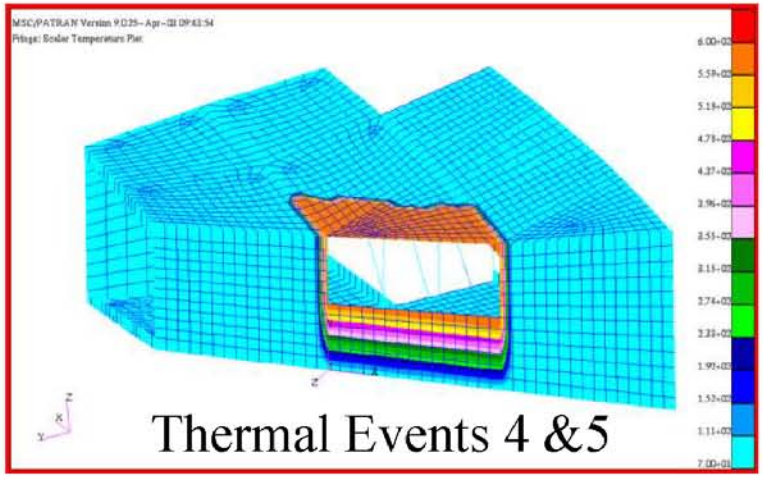
- Thermal events analyzed continued…
  4. Assume burn through on upper half WLE spar web
     - Assumed 600°F on upper WLE cap, wing skin, and wing ribs up to 16 inches from WLE
     - Assumed linear temperature distribution of 600°F to 70°F from edge of burn through (middle of WLE web) to bottom WLE cap
     - 70°F on rest of structure
  5. Assume burn through on upper half WLE spar web and spar cap
     - Assumed 600°F on upper wing skin and wing ribs up to 16 inches from WLE
     - Assumed linear temperature distribution of 600°F to 70°F from edge of burn through (middle of WLE web) to bottom WLE cap
     - 70°F on rest of structure

Thermal Event Temperature Distributions









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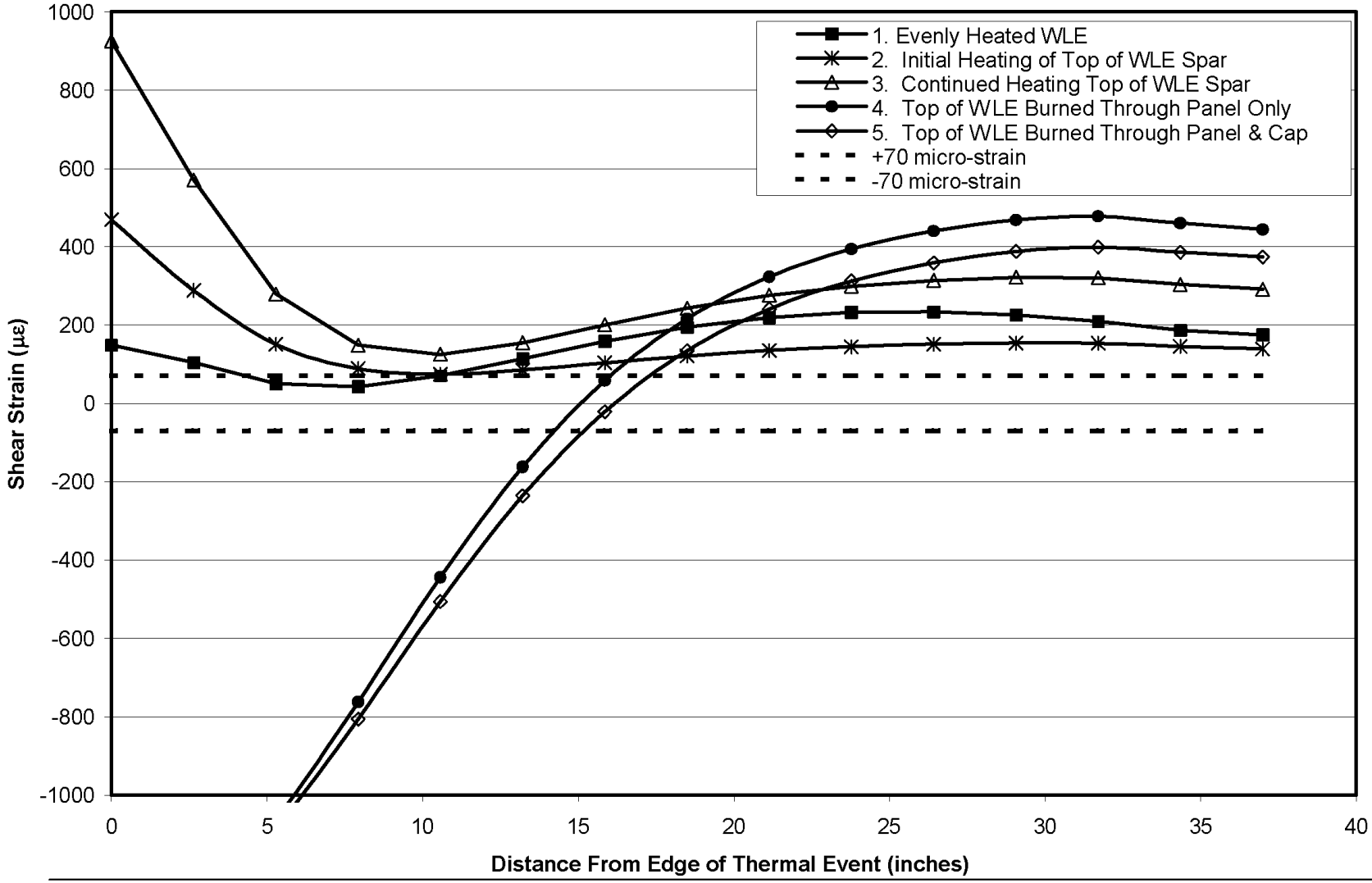
Shear Strain Results Along Midspan of WLE Spar



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Thermal Event Can Cause Increase in Shear Strain Magnitude

- **Results**
  - **Thermal event #1**
    - **Increase in shear strain magnitude along middle of WLE from edge of thermal event outward**
    - **Little change in strain magnitude in region outside of thermal event**
    - **No change in sign**

Unsymmetric Thermal Event Creates Significant Shear Strain Magnitude Increase

- **Results Continued…**
  - **Thermal event #2**
    - **Significant Rise in shear strain magnitude near thermal event boundary**
    - **Reduction in shear strain magnitude with increased distance from thermal event boundary**
      - Shear strain magnitude changes little at distances ≥ 18 inches from thermal event boundary
    - **No change in sign**
  - **Thermal event #3**
    - **Significant rise in shear strain magnitude near thermal event boundary**
    - **Reduction in shear strain magnitude with increased distance from thermal event boundary**
      - Shear strain magnitude changes little at distances ≥ 18 inches from thermal event boundary
    - **Similar trend to initial heating, magnitude of strain increases**

WLE Burn Through Can Cause Shear Strain Sign Reversal

- **Results Continued…**
  - **Thermal event #4**
    - **Reversal in sign of shear strain**
      - For distances ≤ 15 inches from thermal event boundary strain sign is negative
    - **Shear strain from 15 to 19 inches is less than undamaged structure**
    - **Significant rise in shear strain magnitude near thermal event boundary**
    - **Decrease in shear strain magnitude with increased distance from thermal event boundary**
      - Shear strain magnitude changes little at distances ≥ 26 inches from thermal event boundary

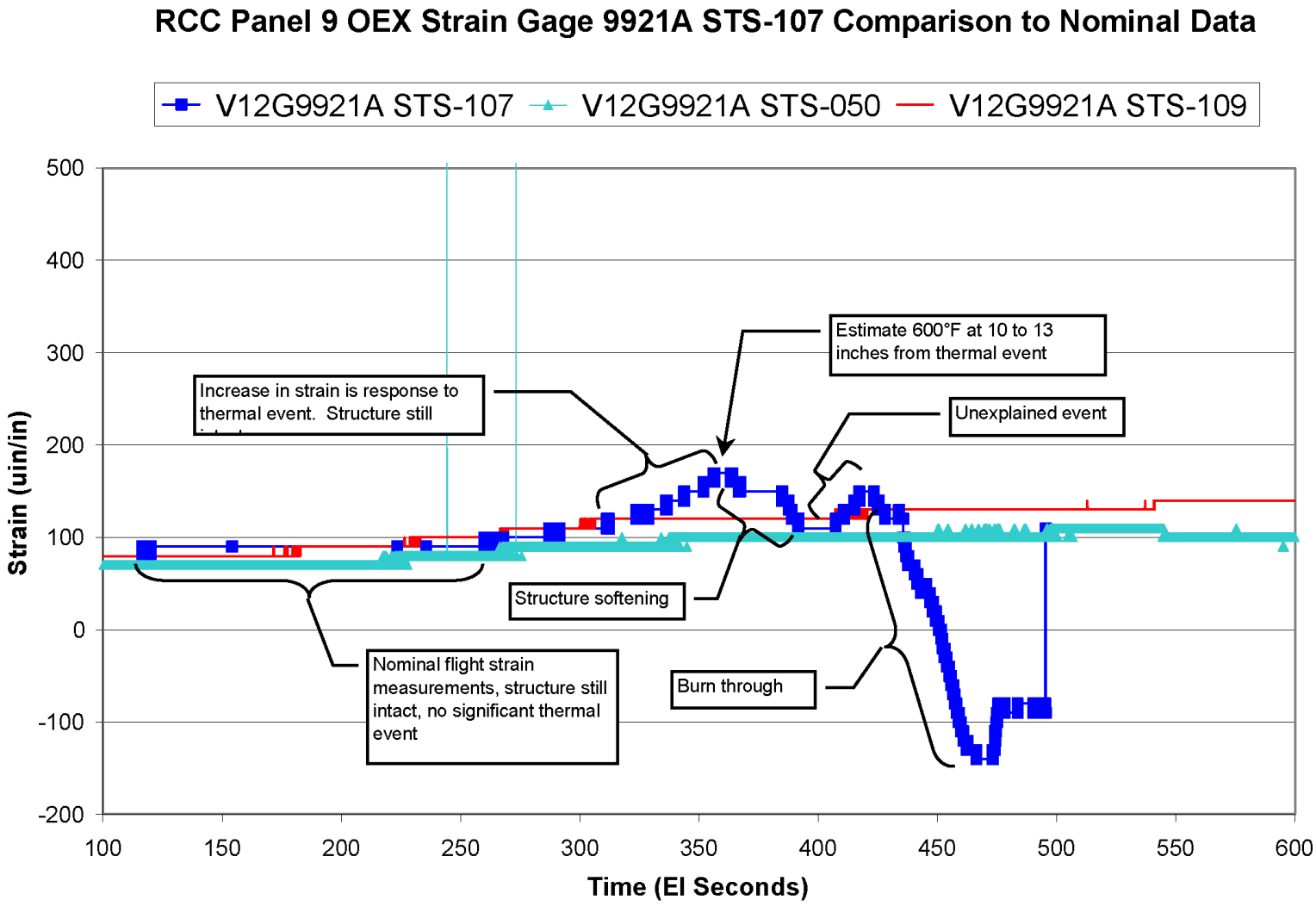
Thermal Event #5 Results

- **Results Continued…**
  - **Thermal event #5**
    - **Further reduction of shear strain from thermal event #4**
    - **Reversal in sign of shear strain**
      - For distances ≤ 16 inches from thermal event boundary strain sign is negative
    - **Shear strain from 16 to 23 inches is less than undamaged structure**
    - **Significant rise in shear strain magnitude near thermal event boundary**
    - **Decrease in shear strain magnitude with increased distance from thermal event boundary**
      - Shear strain magnitude seems to be constant at distances ≥ 26 inches from thermal event boundary

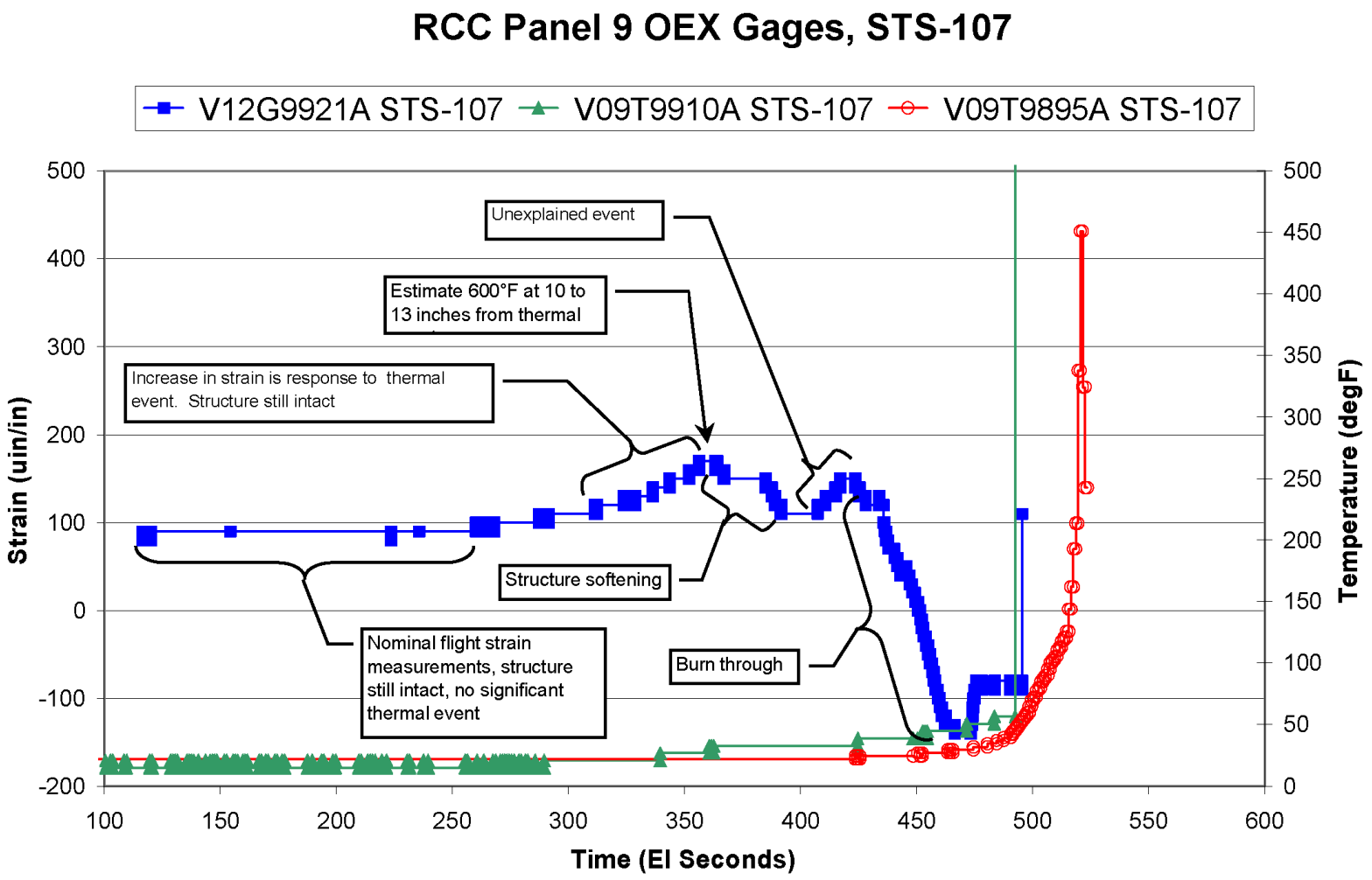
Burn Through Needed for Strain Sign Reversal

- **Possible scenario**
  - **Partial breech in WLE TPS allows plasma impingement on WLE spar**
    - **Causes general temperature increase on WLE panel and cap**
    - **Shear strain readings begin to increase**
  - **Upper WLE panel and spar subjected to primary heating**
    - **Creates temperature gradient on WLE spar from top to bottom**
    - **WLE shear strain gage readings continue to increase**
  - **Upper WLE spar panel burn through**
    - **Shear strains are reduced in region around thermal event causing a strain sign reversal**
      - Panel burn through relieves thermal stresses

Scenario Description Overlay With Nominal Strain Gage Data

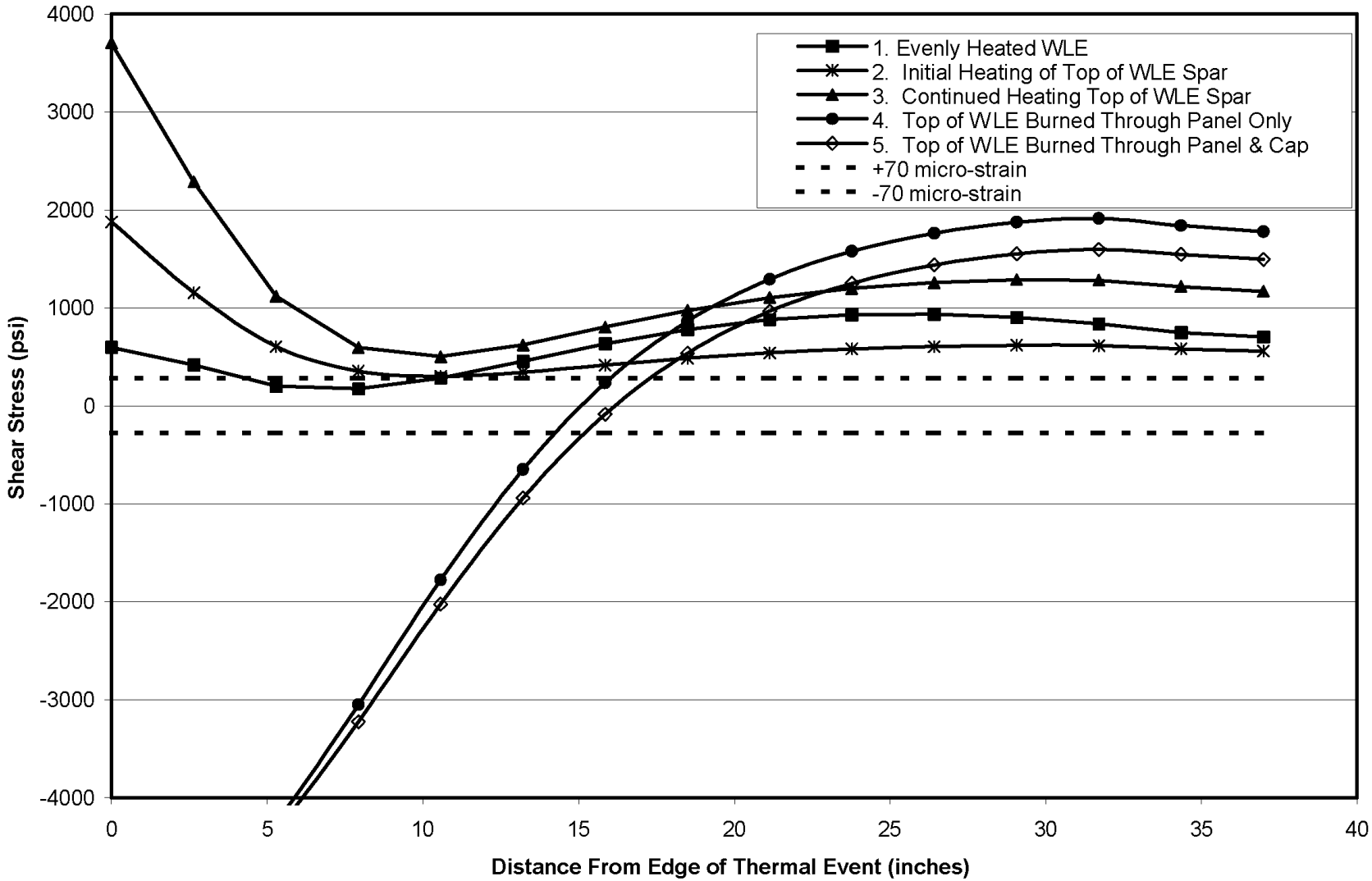


Scenario Description Overlay With Thermal Flight Data



Backup

Shear Stress Results Along Midspan of WLE Spar



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