# STS-28 R
# Early Boundary Layer Transition

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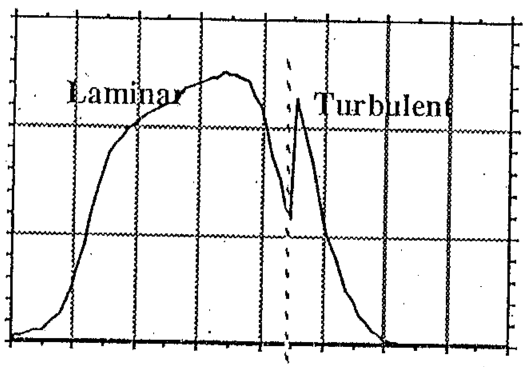
## Background

- **Boundary Layer Transition from Laminar to Turbulent Flow**
  - **Will Always Occur**
    - Function of many parameters : Reynolds number (air **density**, **velocity**, **viscosity**); geometry (configuration, angle of attack, **location** on vehicle, vehicle **roughness**); boundary layer (heat transfer); freestream disturbances; vehicle vibrations
    - Time of transition (for same entry trajectory) primarily dependent on vehicle roughness
    - Roughness, commonly referred to as $K_{eq}$ or, "equivalent roughness", is divided into two types:
      - **Discrete** roughness - One single large protuberance results in boundary layer transition
      - **Distributed** roughness - Many small protuberances results in boundary layer transition

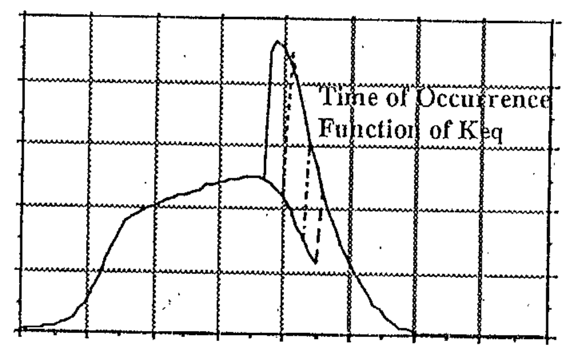
- Time of Transition
  - Most directly determined by the tile surface temperature response

Temp.




Time

Temp.

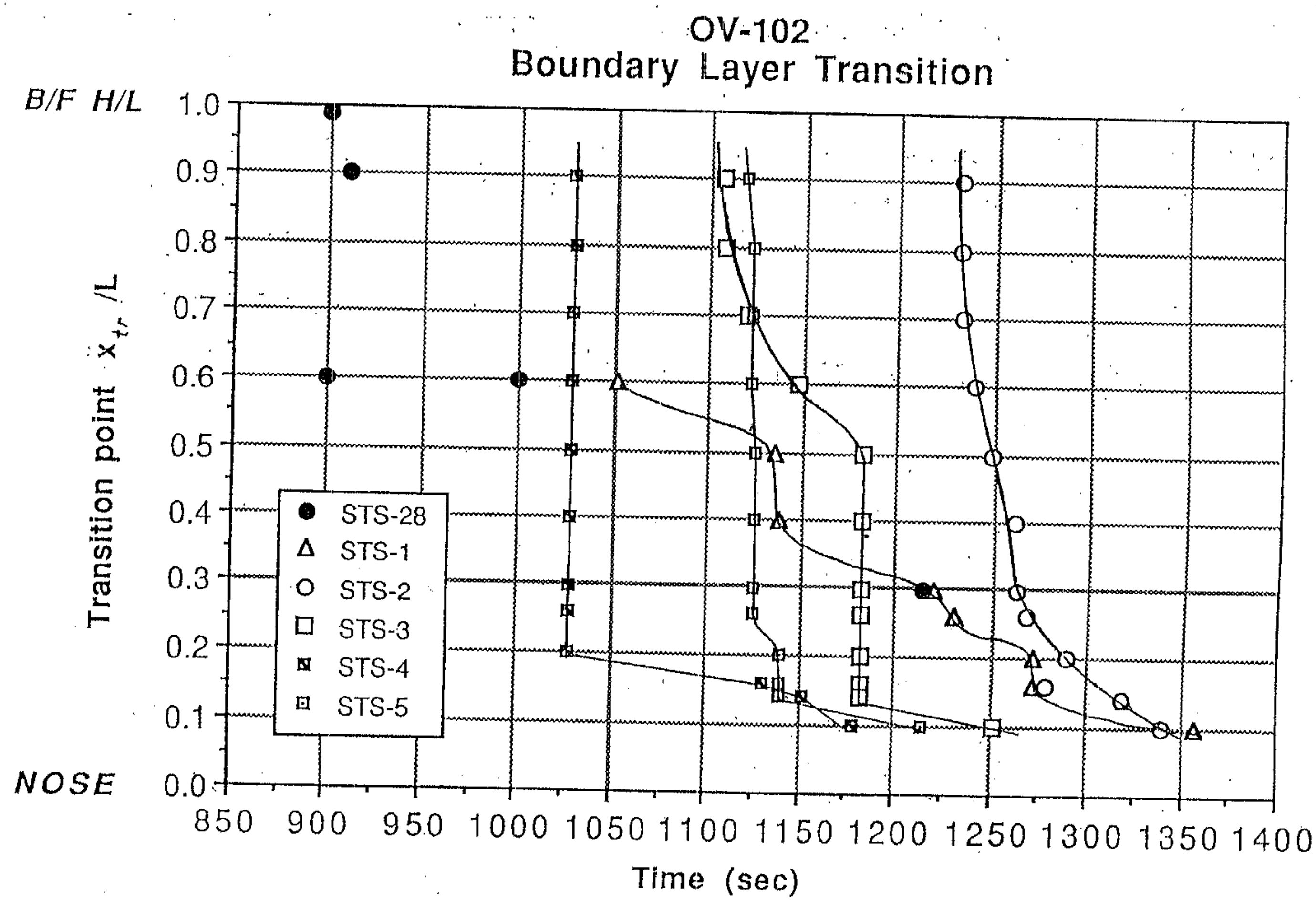



Time

  - Indirectly from X-Axis accelerometer data (most times questionable)

- **Effects of Transition Time**
  - Early time results in more heat load to the structure (all other parameters being equal ; i.e. ; weight, C.G. , orbit inclination, angle-of-attack, cross range, and whether it is an ascending or descending node entry)
  - Heat load to the structure is a function of temperature and time
  - Early transition/heat load is a second or third order effect to structural thermal gradients (thermal stress)
  - Early time results in higher turbulent flow peak temperatures

- Transition sometimes occurs at one time over the total vehicle length, while other times it begins at the aft portion of the vehicle and moves forward



# Transition Time at the Most Consistent Forward and Aft Surface Thermocouple Locations

| STS | OV | FWD | AFT |
|---|---|---|---|
| | | (Sec. after Entry Interface) | |
| 1 | 102 | 1225 | 1060-1140 |
| 2 | 102 | 1260 | 1235 |
| 3 | 102 | 1180 | 1160 |
| 4 | 102 | 1025 | 1025 |
| 5 | 102 | 1125 | 1125 |
| **28** | **102** | **1215** | **900** |
| 26 | 103 | 1135 | 1115 |
| 29# | 103 | 1115 | 1110 |
| 27*# | 104 | ------ | 1050 |
| 30 | 104 | ------ | 1210 |
| 34# | 104 | ------ | 1115 |

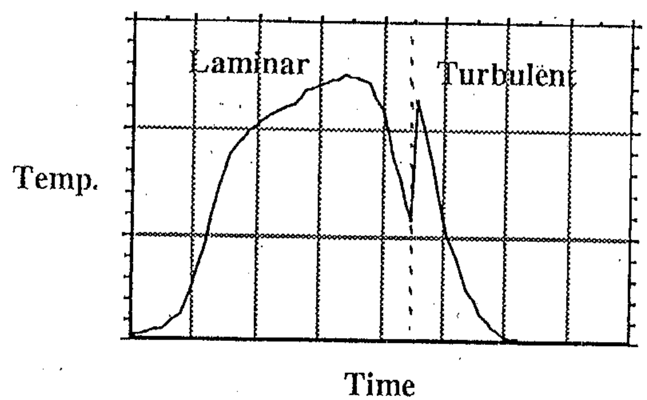
* Massive ascent damage

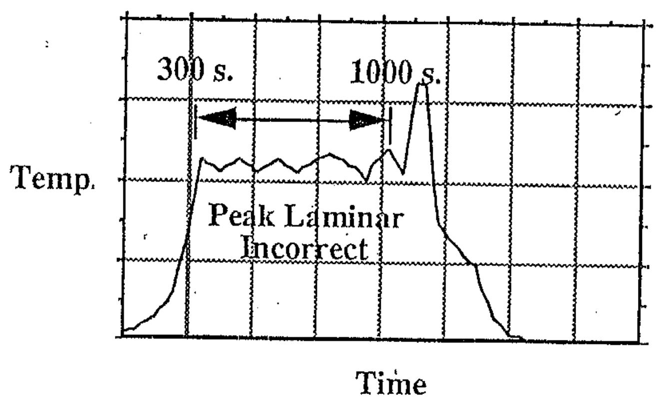
# Turbulent peak temperatures greater than laminar peak temperatures

- Tile Surface Temperature Data (lower surface forward of elevon and body flap hinge lines)
  - STS-1 through STS-5 had approximately 75 tile surface thermocouples
    - Peak laminar temperatures were always greater than peak turbulent temperatures except near the control surfaces (which are affected by control surface movement). Note: STS-1 and STS-4 laminar peak temperatures were not recorded
    - All data consistent, but transition time varied from 1025 to 1250 seconds
  - From STS-6 through 61-C there were no tile surface temperature measurements activated forward of the control surfaces
  - STS-26 through STS-34
    - Activated measurement locations on each vehicle were different with only one common location
    - Turbulent peak temperature was greater than laminar peak temperature on STS-27,34, and possibly 34 (But not to the magnitude of 28) indicating earlier transition time

• **Tile Surface Data (continued)**

- Some data, during peak heating, is not correct (or improperly calibrated) and some measurements were not working




- There are no measurements functioning on the RH wing
- Program plan is to have 25 common surface temperature measurements on each vehicle (14 lower surface)
- Present status of the 14 lower measurements:

| | OV-102 | OV-103 | OV-104 | OV-105 |
|---|---|---|---|---|
| - Installed and functional | 7 | 5 | 3 | 14 |
| - Installed and not funct. | 2 | 0 | 0 | (in line) |

- Gap Fillers
  - **Purpose of Gap Filler**
    - Primarily used to protect the filler bar and structure from exceeding allowable temperatures in high pressure gradient locations (Elevons and Body Flap)
    - Also used to prevent local heating conditions, resulting from incorrect tile installation
    - Provide the design equivalent roughness requirements based on step and gap measurements (very limited use; by exception)
  - **Types of Gap Filler**
    - Ames - RTV impregnated AB312 cloth (one to four plies allowed & used to fill gaps for unacceptable $K_{eq}$ conditions)
    - Pillow Type - AB312 cloth filled with Alumina (Safill) material (0.20 inches) both open and captive application
    - Mini Pillow (Pad Type)- Same as pillow but less than 0.20 inches thick (Used for unacceptable gaps)

## Background (Continued)

- **Design Gap Fillers**
  - All design pillow gap fillers forward of the E.T. doors are captive type
  - All design pillow gap fillers have part numbers
  - Many Ames gap fillers are used in the regions of the MLGD's, FWD ET, NLGD and are design gap fillers by drawing and do not have part numbers
- **Non-Design Gap Filler**
  - Non-design Ames and thin pillow (Pad type) gap fillers are installed as required to correct potential local overheating conditions, tile-to-tile $K_{eq}$ conditions and previous Cat 1 and Cat 2 charred filler bars
    - Installation is recorded by KSC paper
    - No practical way to retrieve and track non-design Gap Fillers

- **Gap Filler Installation**
  - Rockwell Specification ML0601-9024 "G"
    - Process 601 for pillow gap fillers
      - Perform Step and Gap
      - Build Mylar Patterns
      - Perform Tile Lock (Hold the Gap)
      - Perform Pre-fits, Verify OML Height
      - Perform Friction Test
      - Inspect Bonding Surface
      - Clean and Prime
      - Bond Gap Filler
      - Perform Bond Strength Test

- **Gap Filler Installation (Continued)**
  - Process 602 for Ames Gap Fillers
    - Perform Step and Gap
    - Perform Prefits, Verify OML Height
    - Verify Resultant Effective Gap and Total Number of G/F
    - Inspect Bonding Surface
    - Clean and Prime
    - Bond
    - Perform Pull Test
    - Record Number of Layers
    - Record Resultant Gap

# •STS-28

## •Sequence of Evidence

- Glazed tiles in front of R.H. E.T. door (not normal in this location)
- Report of protruding and missing non-design pillow and Ames gap fillers (not unusual, except there were some missing forward of the E.T. doors and there were a larger than usual quantity found on the runway)
- O.I. structural temperature rise was greater that STS-9 (first quantitative evidence of additional heat load for a similar entry)
- MADS tile surface temperature data showed early transition on the aft 60% of the Orbiter, while the nose transition was normal-to-late (>1200 seconds)
- Larger than usual quantity of category 1, 2, and 3 filler bar chars (to be expected with an additional 5 minutes of exposure to turbulent heating temperatures)

# • STS-28 (Continued)

- **Most probable cause of early boundary layer transition is protruding gap fillers on the lower forward surface**
  - Several protruding non-design pillow and Ames gap fillers were evident after landing
  - More than usual number of gap fillers gap fillers found on the runway near touchdown (Some expected to fall out; installed after MLGD closure to tighten the thermal barrier)
  - Tile step and gap within specification or MR criteria
    - OV102 **pre flight measured** $K_{eq}$; 0.137 (Forward of 30%)
      - OV103 (STS-26); $K_{eq}$=0.135
      - OV104 (STS-30); $K_{eq}$=0.123
    - OV 102 **post flight** transition Keq; 0.128 (forward of 30%), Keq of 0.300 (aft 60%)
      - OV103; $K_{eq}$=0.127
      - OV104; $K_{eq}$=0.115

- STS-28 (Continued)

  - **Why were protruding portion of gap fillers not burned off during entry?**
    - Gap fillers utilize AB312 glass cloth as the basic material which will survive temperatures in excess of 1800 ° F
    - Local tile surface laminar and turbulent temperature data shows less than 1800 °F
    - Local protuberance heating was probably not high enough to melt or ablate the gap filler material but could burn out or soften the RTV of the Ames gap fillers, which may allow them to then lay over, as were found post landing

- STS-28 (Continued)

  - **Questionable "Double Transition" Data and Transition Time (V07T9478, Centerline and V07T9480 port side at same X location)** **(See Next Page)**

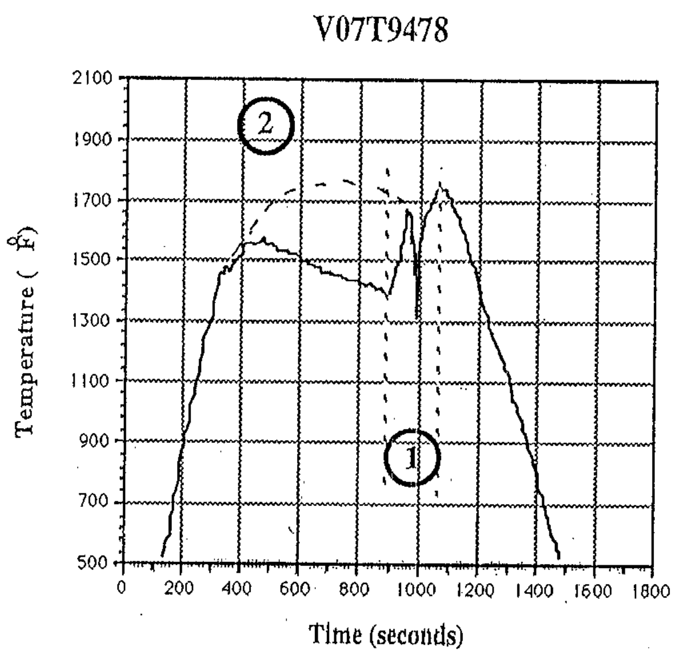
    - (1) - If data is "good" during this time interval, it shows that transition from laminar to turbulent flow occurred at approx. 900 seconds, then went back to laminar flow at 1000 seconds for V07T9478 and 950 seconds for V07T9480, then returned to turbulent flow.

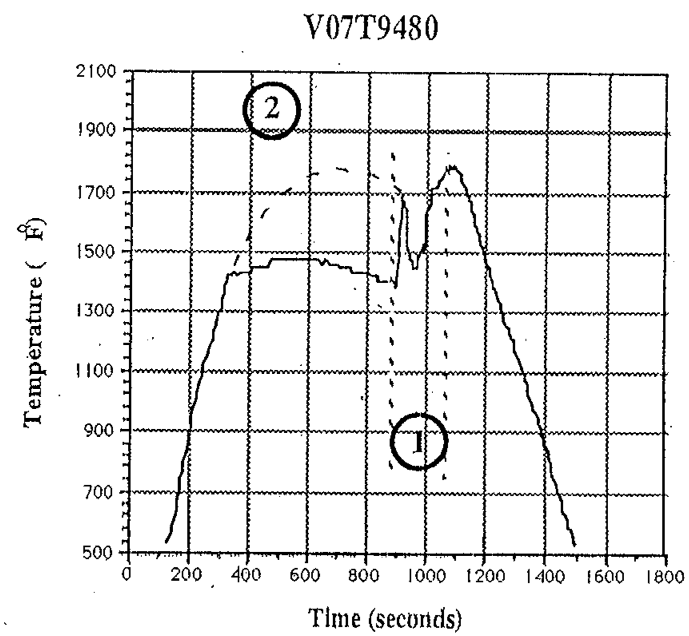
      -May possibly result from protruding AMES gap fillers, causing the first transition to occur; then (after burning out or softening the RTV) the gap filler layed over, allowing return to laminar flow before the final transition to turbulent flow

OR - (2) - If the data is "not good", but really reacts as shown by dashes, it negates the first transition time

**<u>BUT</u>** Laminar peak temperatures would be higher than ever recorded in these locations and, Thermal Analysis shows that structural temperatures would not correlate with the higher laminar temperatures

- STS-28 (Continued)




## STS-28 Flight Data

- STS-28 (Continued)
  - **Was this the only STS flight that had unusually early transition?**

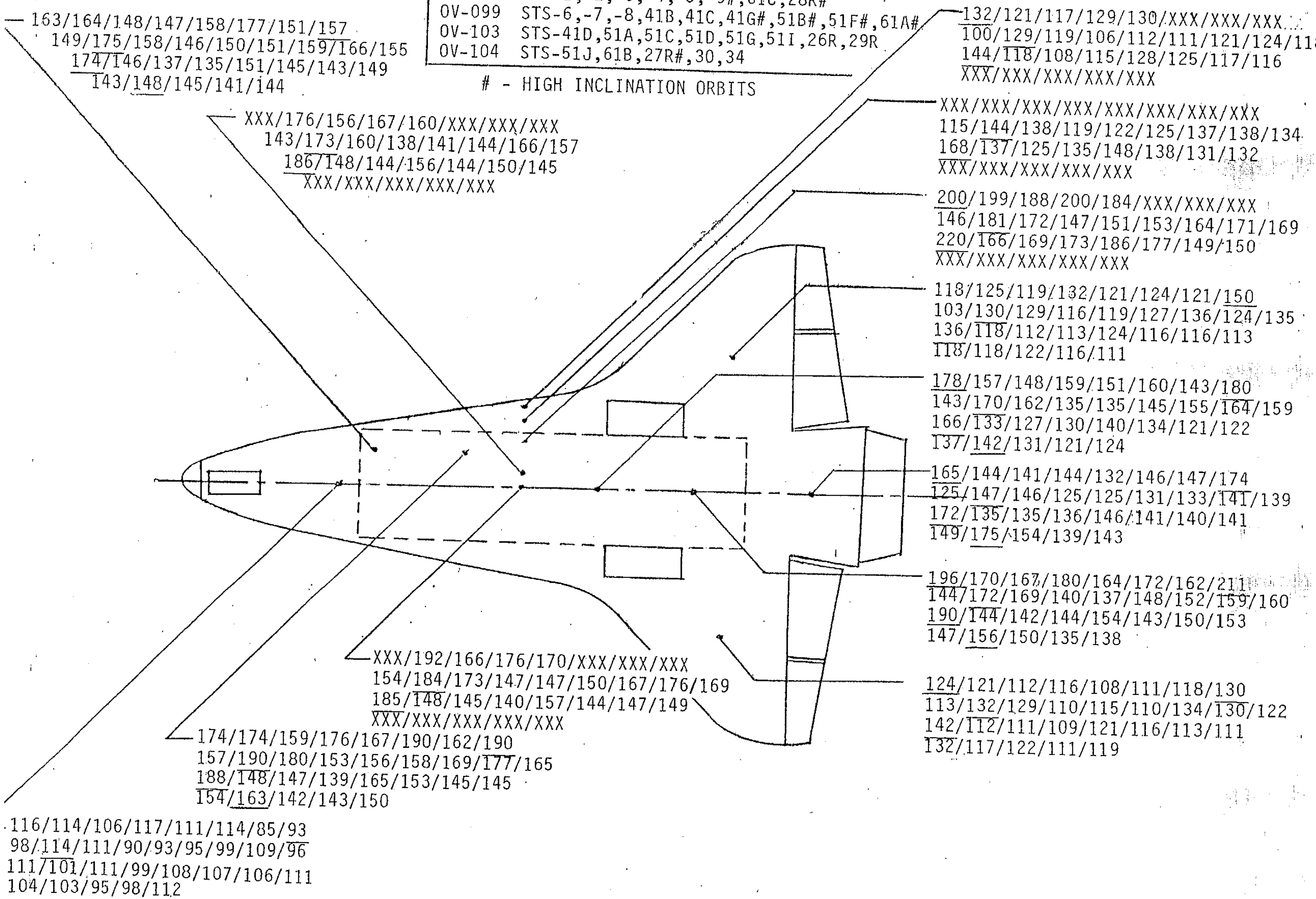
    **Probably ... "YES". But possibly STS-1 and STS-4, in the aft**

    - Only STS-1 through 5 and STS-26, 27, 28, 29, 30, and 34 had surface thermocouples to quantitatively establish time of transition
    - No other post-flight landing inspection revealed any evidence of excessive heat load/temperatures such as "above normal" filler bar chars, slumped tiles, etc.
      - Early flights of each Orbiter tended to have more charred filler bars than late flights, since later flights had susceptible gaps progressively filled
    - Operational structure temperature measurements (from which structural temperature rise is obtained) did not show any unexplained/unusual values except indications on flights with no surface thermocouple instrumentation, or no data. Noteably:
      - The second flight of OV-099 (STS-7)
      - The first flight of OV-103 (STS-41D)
      - The second flight of OV-104 (STS-51J)

# ORBITER STRUCTURAL TEMPERATURE RISE DUE TO ENTRY HEATING

| | |
|---|---|
| OV-102 | STS-1,-2,-3,-4,-5,-9#,61C,28R# |
| OV-099 | STS-6,-7,-8,41B,41C,41G#,51B#,51F#,61A# |
| OV-103 | STS-41D,51A,51C,51D,51G,51I,26R,29R |
| OV-104 | STS-51J,61B,27R#,30,34 |

# - HIGH INCLINATION ORBITS



•STS-28 Scenario

- **Protruding Gap Fillers**
  - All gap filler installations prior to lift-off were within specification limits, or MR acceptable (control surface locations)
  - An aerodynamic load, vibration, or other load/force would be necessary to result in protrusion of improperly installed gap fillers
    - SRB and/or SSME ignition - Possibly
    - Ascent Aero - Most likely (Max Q)
    - On-orbit RCS jets - Not likely
    - OMS de-orbit burn - Possibly
    - Entry aero/maneuver - Not likely
  - Would have to have occurred prior to 900 seconds after entry interface
  - Would indicate improper bond/poor workmanship

- **Speculative scenario of what may have occurred goes like this:**
  - Post STS-61C (last previous flight of OV-102 : Jan. 1986)more than 100 gap fillers were added or replaced on the lower surface prior to 51L
  - After 51L, OV-102 underwent major modifications at KSC requiring the installation of approximately 2,000 gap fillers. The most significant being:
    - Elevon cove modification
    - Replacement of negative margin tiles
    - Installation of the Chin panel
  - A very large quantity of gap fillers were installed late in the OPF flow (343) and 212 installed in the VAB and PAD (**<u>Out of Station Bonding</u>**)
  - A large turn over of TPS technicians also occurred over the 3 1/2 years time period, leaving a skeletal force of experienced personnel
  - Certification and training for gap filler installation is one of the easiest to obtain. May have utilized these personnel
  - Pull string verification was partially subjective for the STS-28 flow

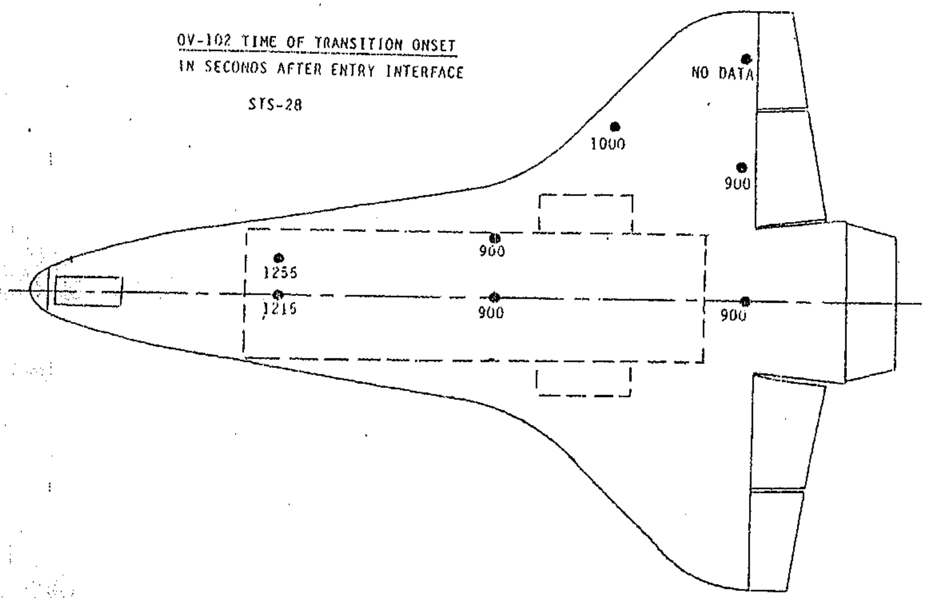
## •Summary

- Early boundary layer transition did occur on the aft 60% of the Orbiter
- The Most Probable Cause of the early transition is protruding gap fillers
- The gap filler installation specifications are adequate to assure proper gap filler bonding IF all of the steps are performed correctly
- Improper or inadequate gap filler bond integrity depends on the quality of the installation
- Protruding gap fillers :
  - Are not a safety of flight concern, unless coupled with another adverse condition
  - Are a turn around work issue

# Back-Up Charts

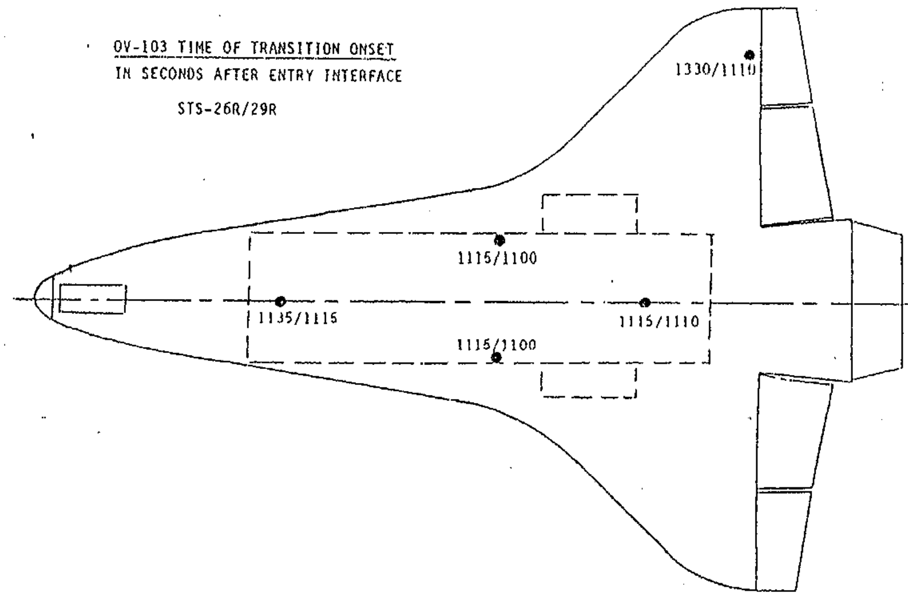
OV-102 TIME OF TRANSITION ONSET
IN SECONDS AFTER ENTRY INTERFACE

STS-28



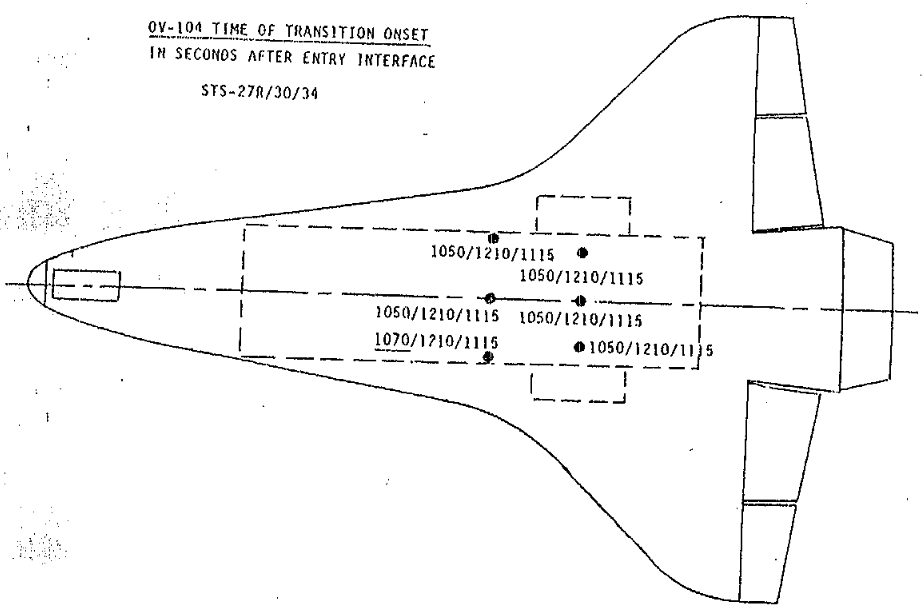

OV-103 TIME OF TRANSITION ONSET
IN SECONDS AFTER ENTRY INTERFACE

STS-26R/29R



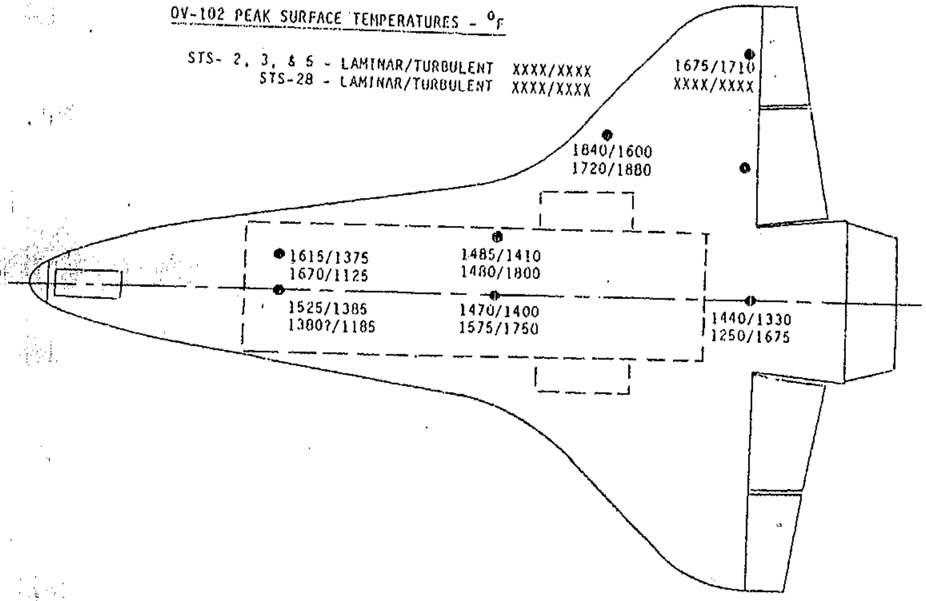

OV-104 TIME OF TRANSITION ONSET
IN SECONDS AFTER ENTRY INTERFACE

STS-27R/30/34



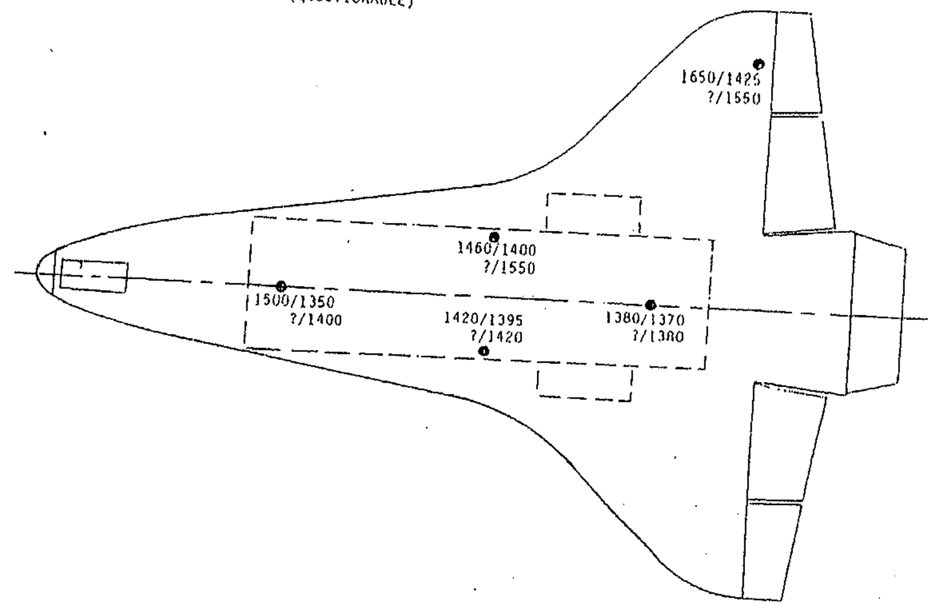
OV-102 PEAK SURFACE TEMPERATURES - °F

STS- 2, 3, & 5 - LAMINAR/TURBULENT XXXX/XXXX
STS-28 - LAMINAR/TURBULENT XXXX/XXXX



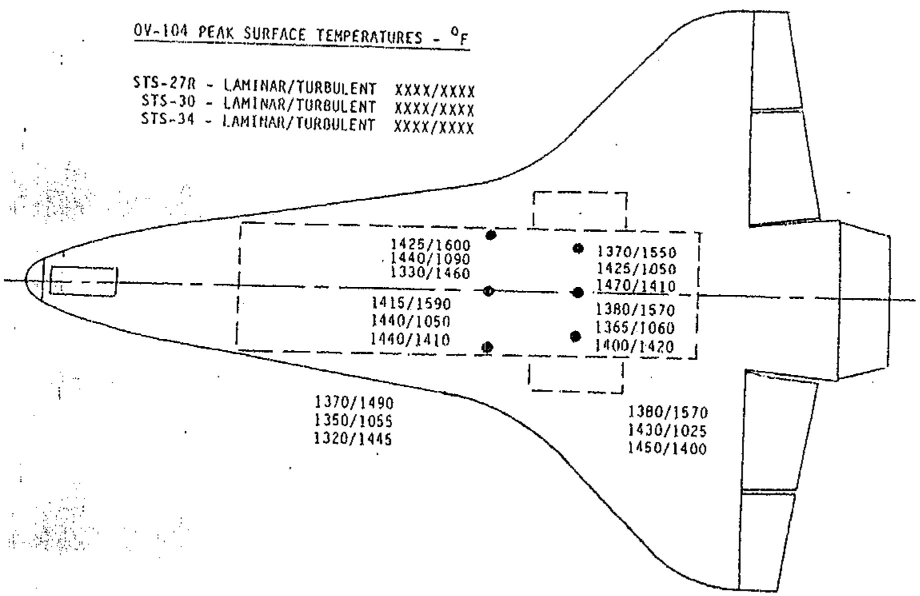

OV-103 PEAK SURFACE TEMPERATURES - °F

STS-26R - LAMINAR/TURBULENT XXXX/XXXX
STS-29R - LAMINAR/TURBULENT XXXX/XXXX
(QUESTIONABLE)

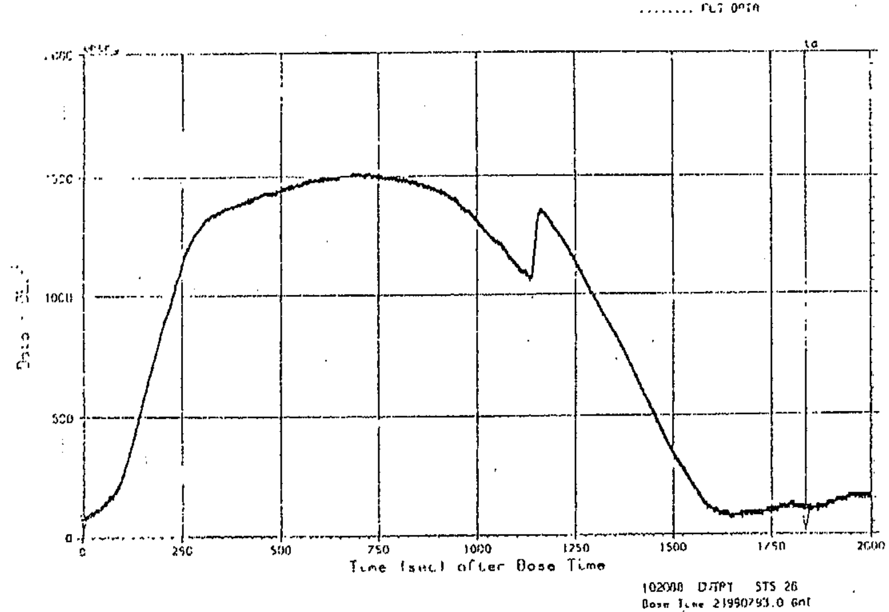



OV-104 PEAK SURFACE TEMPERATURES - °F

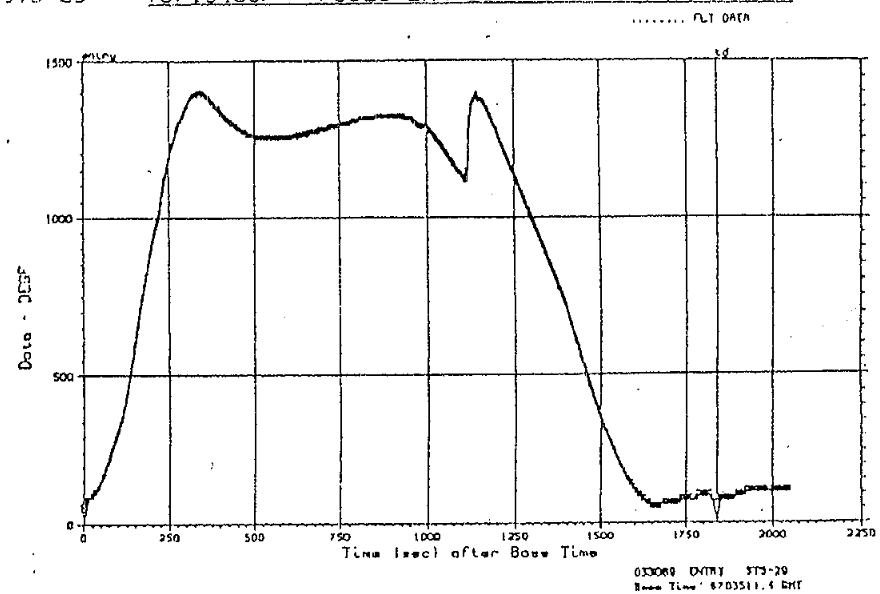
STS-27R - LAMINAR/TURBULENT XXXX/XXXX
STS-30 - LAMINAR/TURBULENT XXXX/XXXX
STS-34 - LAMINAR/TURBULENT XXXX/XXXX



STS-26 V07T9468A FUSLG LWR SURF THERMOCPL BP1300T




STS-29 V07T9468A FUSLG LWR SURF THERMOCPL BP1300T



## FIGURE 3
## ORBITER FLEET TPS INSTRUMENTATION
(EXCLUDING OMS PODS & CHIN PANEL)