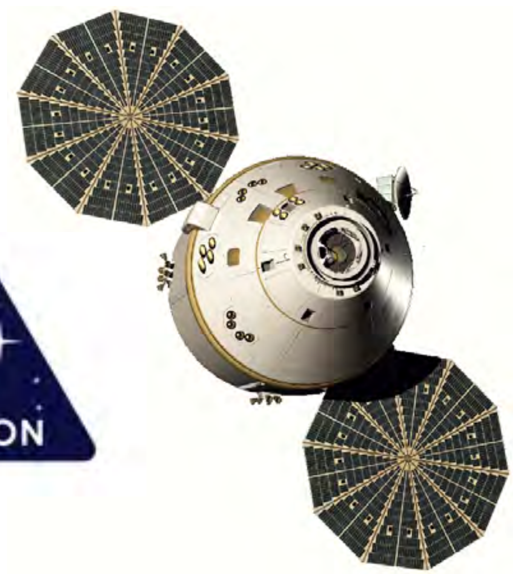
Multi-Purpose Crew Vehicle (MPCV)

Apollo IV (AS-501)
Convective Heating Predictions of Flight Data

MPCV Aerosciences



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Contents

Motivation

Background

Convective Heating Predictions to Flight Data Comparisons

Conclusions

Motivation

- Since the Apollo vehicle was designed, our methodologies for designing the thermal protection system (TPS) to protect humans from the extreme temperatures of re-entry have changed significantly.
- MPCV Aerosciences is currently in the process of designing a capsule similar to, but different from, the Apollo Command Module. We can utilize the Apollo IV flight data to assess our current tools and methodologies, and extrapolate the results to MPCV.
- One critical area of concern is the aftbody separated region convective heating environments. Apollo designers used ablative TPS in this area, whereas MPCV is using reusable TPS. The ablative TPS can withstand much more severe environments.
- The following analysis evaluates the computational fluid dynamics (CFD) best practices for the MPCV Aerosciences Aerothermal Database in comparison to Apollo IV flight data.
- The time history heat fluxes of 17 aftbody calorimeters from Apollo IV are available for comparison to current Database methodologies.

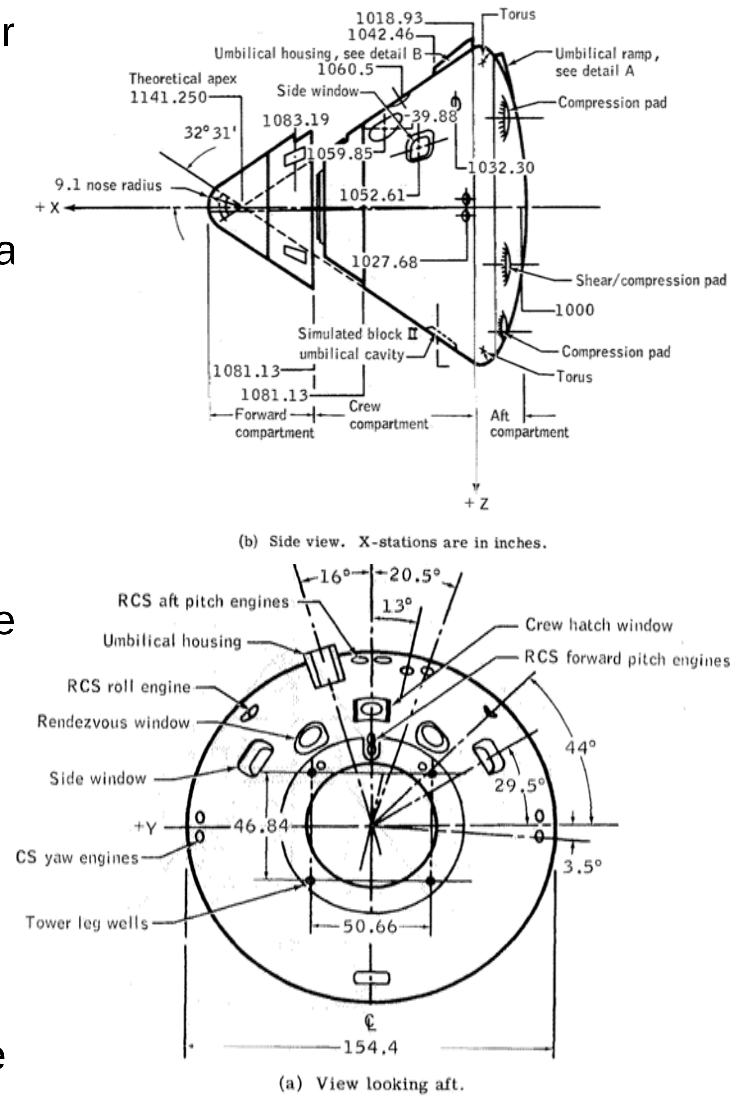

Figure 9. - Command Module 017 external configuration. All linear dimensions are in inches.

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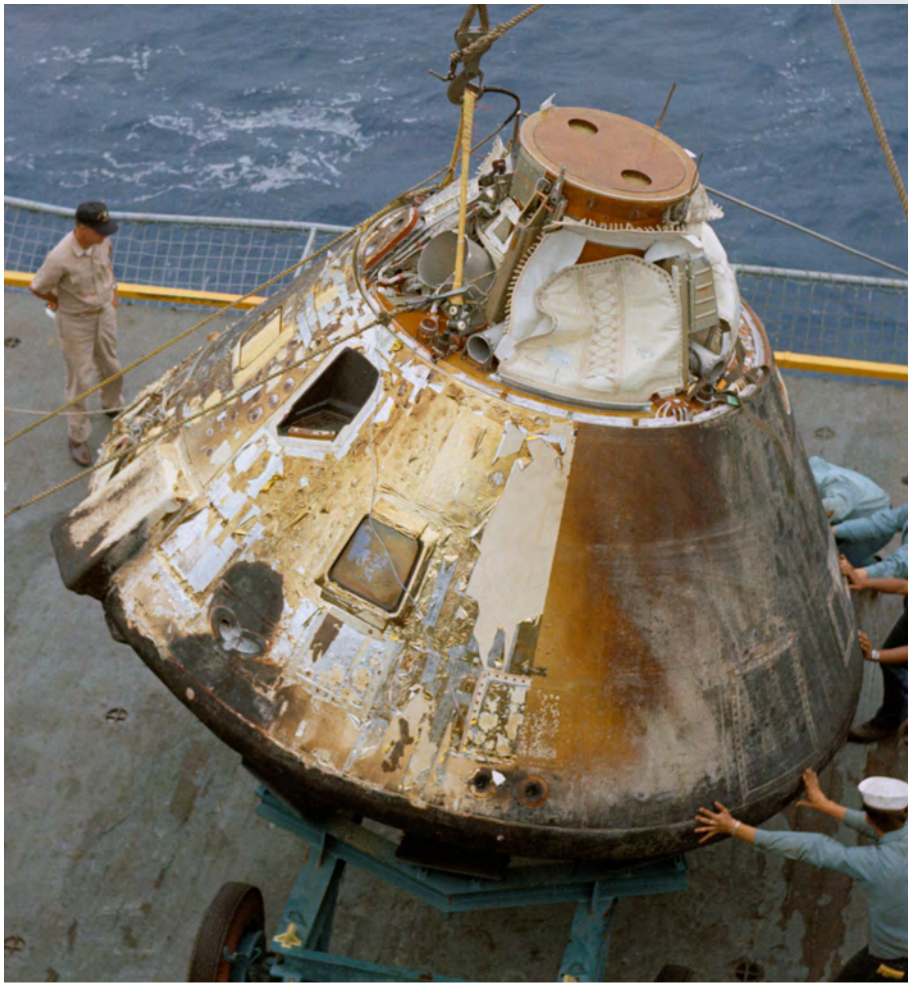
Apollo Flight Testing (up to Apollo VI)

:

Mission	Spacecraft	Description	Launch date	Launch Site
PA-1	BP-6	First Pad Abort	Nov 7, 1963	White Sands
A-001	BP-12	Transonic Abort	May 13, 1964	White Sands
AS-101	BP-13	Nominal launch and exit environment	May 28, 1964	Cape Kennedy
AS-102	BP-15	Nominal launch and exit environment	Sept 18, 1964	Cape Kennedy
AS-002	BP-23	Maximum dynamic pressure abort	Dec 8, 1964	White Sands
AS-103	BP-16	Micrometeoroid experiment	Feb 16, 1965	Cape Kennedy
A-003	BP-22	Low-altitude abort	May 19, 1965	White Sands
AS-104	BP-26	Micrometeoroid experiment and SM RCS launch environment	May 25, 1965	Cape Kennedy
PA-2	BP-23A	Second pad abort	June 29, 1965	White Sands
AS-105	BP-9A	Micrometeoroid experiment and SM RCS launch environment	July 30, 1965	Cape Kennedy
A-004	SC-002	Power-on tumbling boundary abort	Jan 20, 1966	White Sands
AS-201	SC-009	Supercircular entry with high heat rate	Feb 26, 1966	Cape Kennedy
AS-202	SC-011	Supercircular entry with high heat load	Aug 25, 1966	Cape Kennedy
Apollo IV/ AS-501	**CM-017**	**Supercircular entry at lunar return velocity**	**Nov 9, 1967**	**Cape Kennedy**
Apollo 6/ AS-502	CM-020	Supercircular entry at lunar return velocity	April 4, 1968	Cape Kennedy

Recovery Photos of Apollo IV

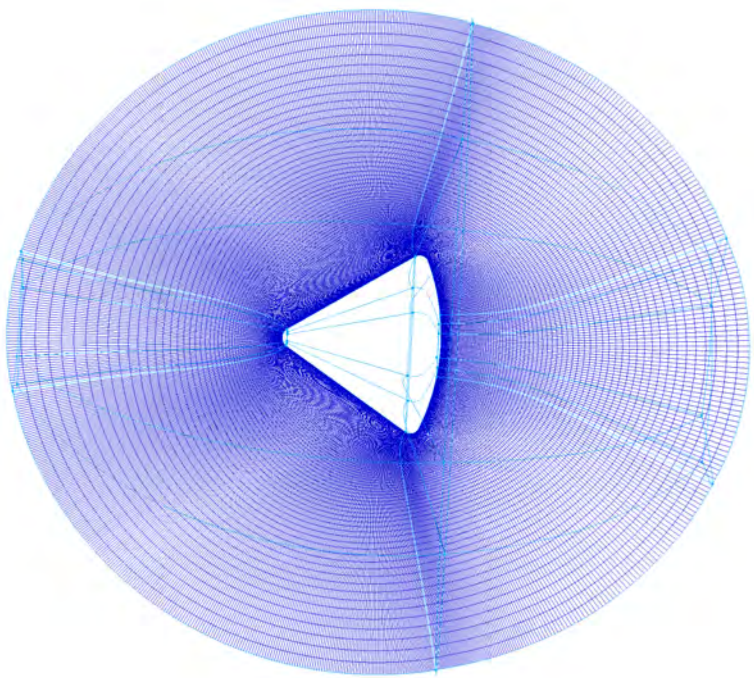


Re-Entry Conditions - The Apollo IV Capsule entered at an angle of attack of 156.84 degrees with a velocity of 36545 ft/s (11.1 km/s) at entry interface (400000 ft).

Apollo IV Capsule Now

*Opposite side of calorimeter locations

CFD Methodology



The grid used for computations was a block structured grid consisting of 16 blocks with 14,285,460 points (107712 surface cells). The grid had 128 off-body points and was a full 360 degree three-dimensional grid.

Data-Parallel Line Relaxation (DPLR)

DPLR is a CFD solver developed at NASA Ames Research Center for hypersonic flow field problems. It is a parallel, full three-dimensional Navier-Stokes CFD solver including models for finite-rate reaction kinetics, thermal and chemical non-equilibrium and ionized flow physics.

- Number of Database Points - 23 solutions
- Flow Types - Laminar and Turbulent using the Baldwin-Lomax turbulence model
- Wall Catalycity - Fully-Catalytic
- Wall Boundary Condition - Radiative Equilibrium Wall
- Surface Emissivity - 0.85
- Atmospheric/Chemistry Model
  - Vel ≤ 8.0 km/s, 5 species air
  - Vel > 8.0 km/s, 11 species air
- Turbulent surface statistics, and points tracked for convergence

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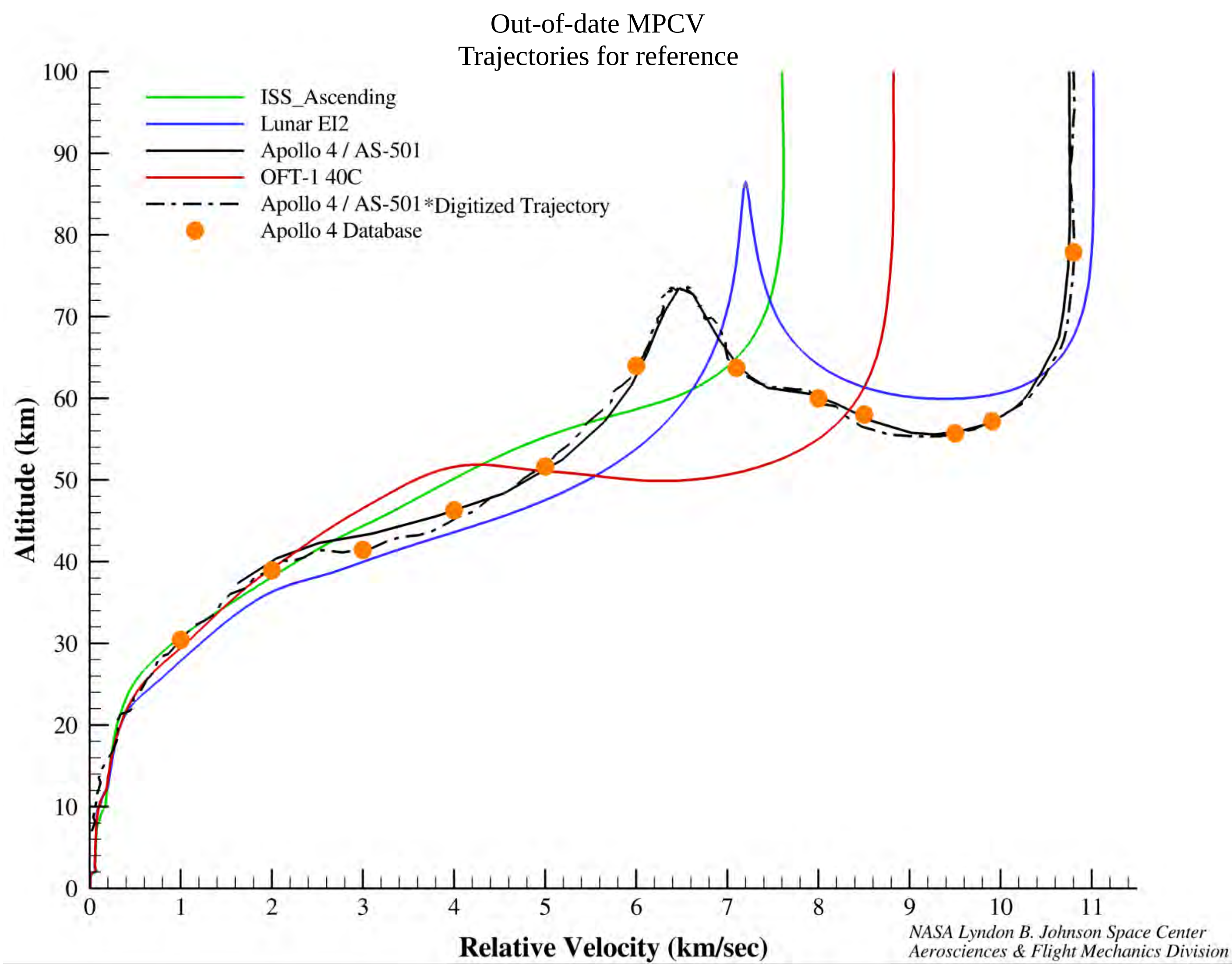
Apollo IV Trajectory and Database Points



Apollo IV (AS-501/CM 017) Geometry

Size - The Apollo Capsule had a maximum diameter of 3.91 meters and the aftbody was a 33° cone.

Features - The Apollo IV backshell was not completely smooth, whereas the grid was smooth. There were RCS engine nozzles (Pitch, Roll and Yaw), a simulated umbilical cavity on the windward centerline, umbilical housing on the leeward centerline, vents, windows, LES tower leg wells, and even two EVA handrails on the Apollo IV backshell. Command Module is currently located at Stennis Space Center.

Surface Coatings - The aftbody heatshield material was Avcoat coated with titanium dioxide paint followed by mylar tape and H-film tape. This means we are unsure of the catalycity and emissivity of the backshell. The windward backshell Avcoat did experience some charring which would be partially catalytic.

- Titanium Dioxide paint – fairly low catalycity[1]
- Virgin Avcoat – highly catalytic, Charred Avcoat – partially catalytic[1]
  - Calorimeters 12-20 - Avcoat appeared to be charred
- Emissivity of 0.85 is typical of carbonaceous ablators[1]
- Calorimeters (constantan foil) – nearly fully catalytic, probably lower emissivity, not in radiative equilibrium

Aftbody Features and Gauge Locations

NASA-S-68-396

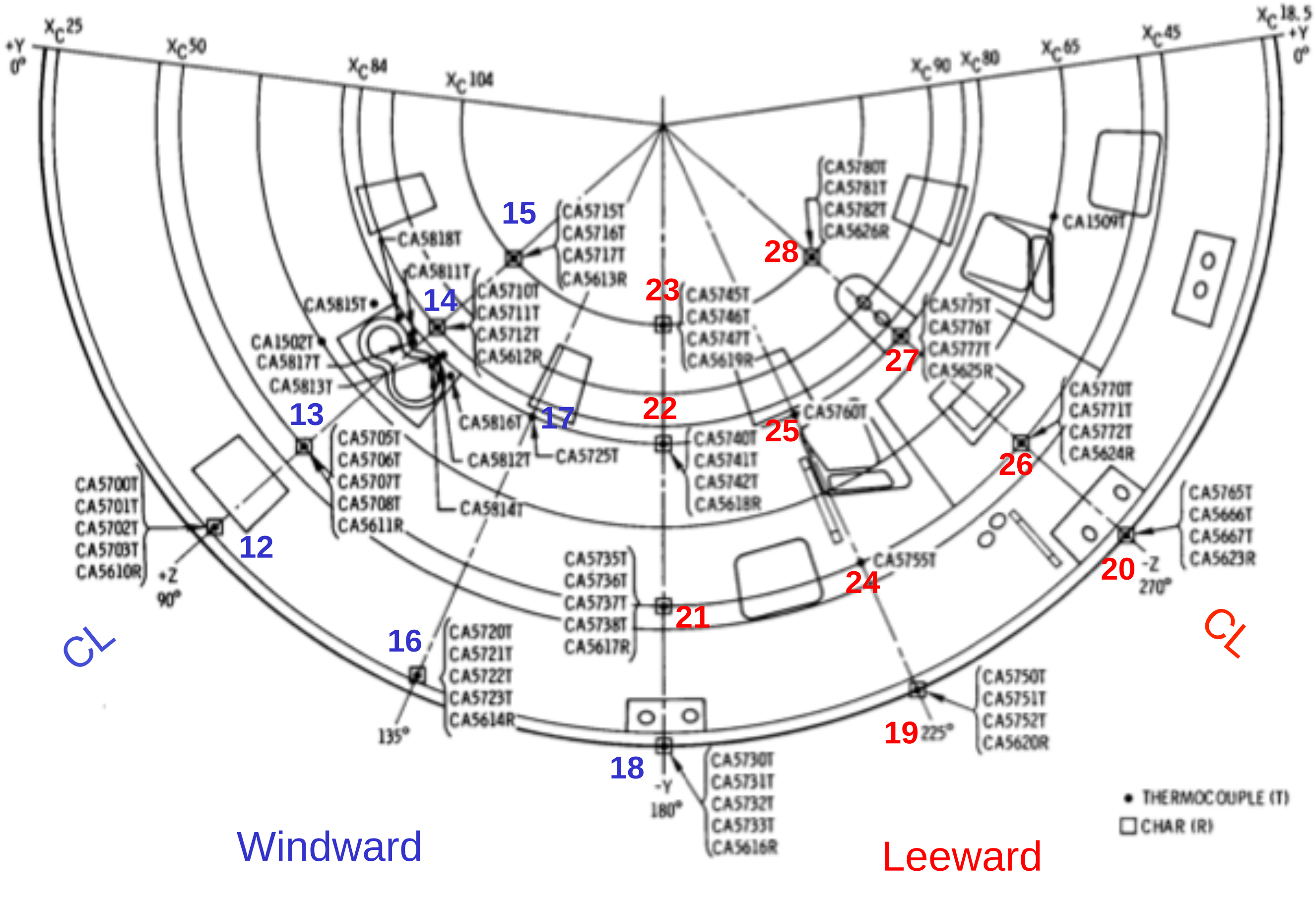
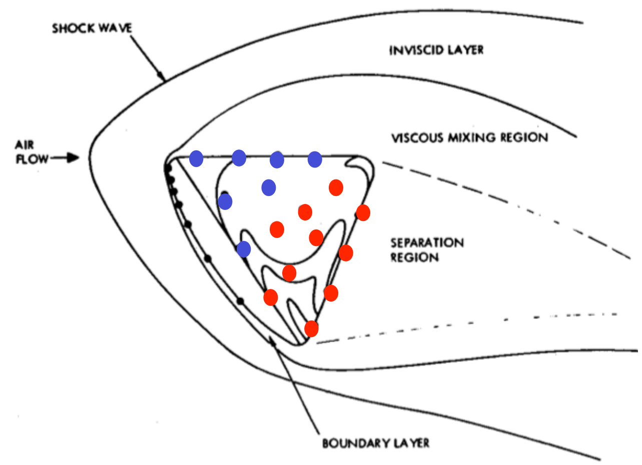


FIGURE 5.4-11. - CONICAL HEAT SHIELD ABLATOR AND ASTRO-SEXTANT AREA TEMPERATURE AND CHAR MEASUREMENTS.



Postflight Calorimeter Pictures

Calorimeter 25

Calorimeter 14

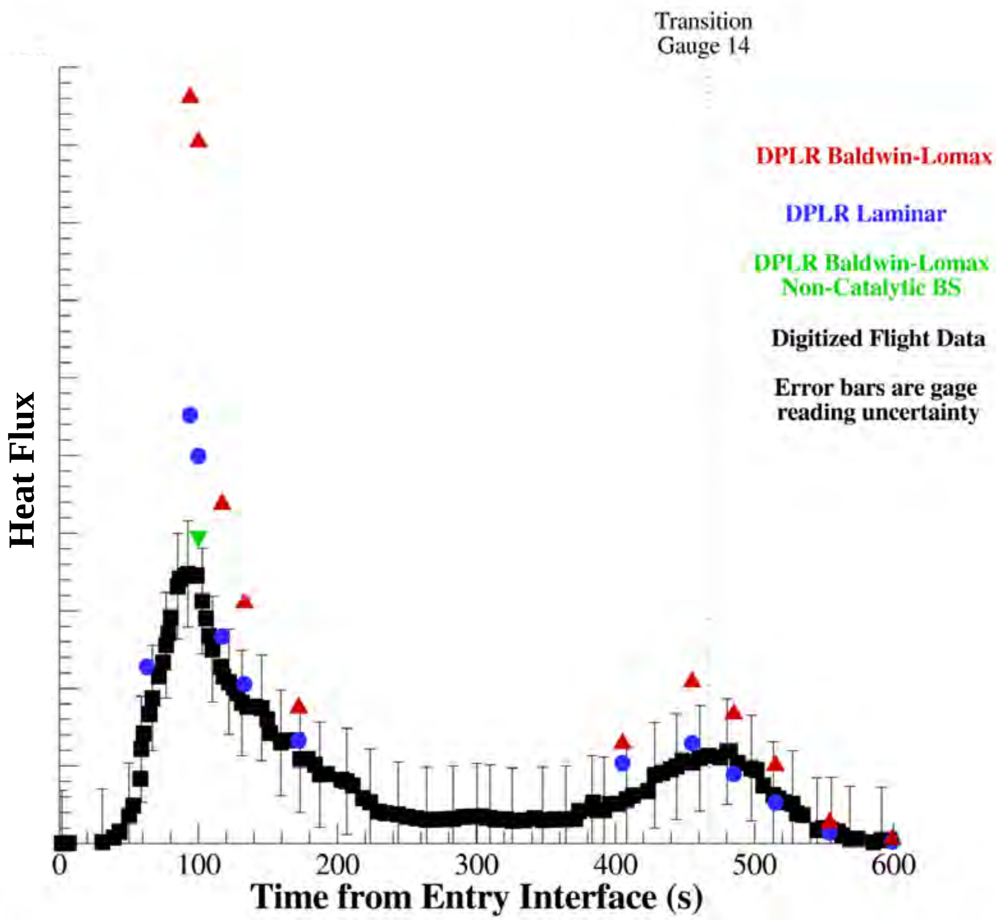
Comparisons of DPLR Results to Flight Data

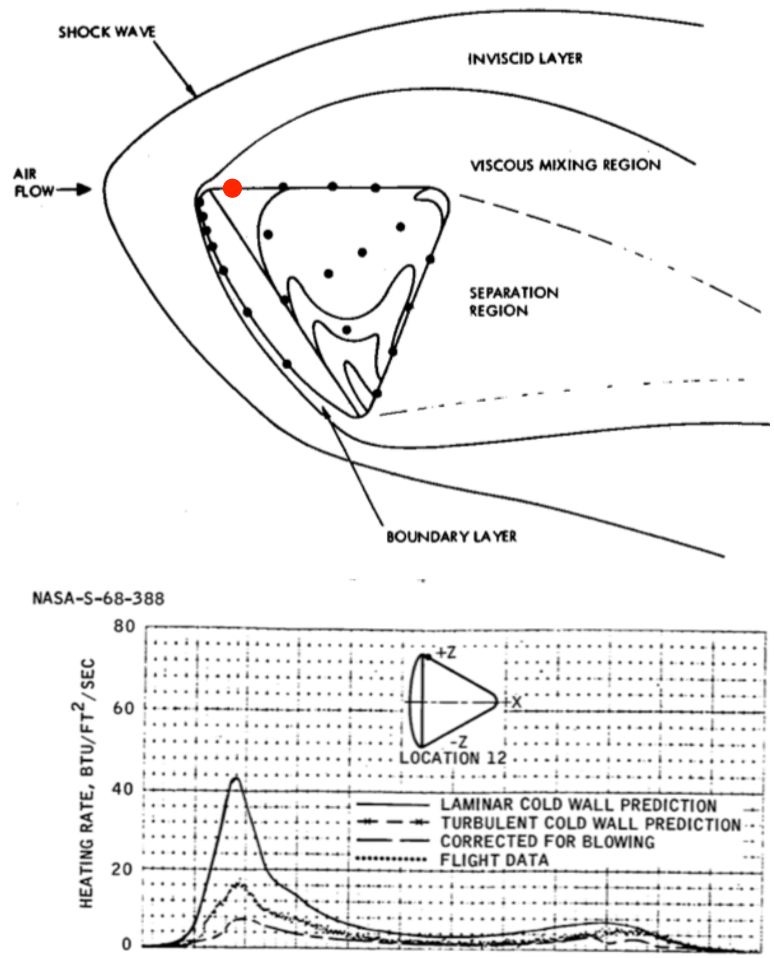
Caveats for Comparisons

- Some error was introduced due to digitizing the flight data from reports. Measurement resolution uncertainty is shown in the error bars, but this does not include other sources of error (such as digitization).
- There is also uncertainty in the BET, and thus the Database solution points chosen for comparisons.
- Gage locations used for data extraction are “pre-installation” locations.
- The DPLR solutions were run on a smooth grid, whereas the flight data includes the influence of features and RCS firings, etc.

Gauge 12 – Windward Centerline

** Reported data uncertainty is ±2% of the range, which is 150 btu/ft^2/s (so 3 btu/ft^2/s)

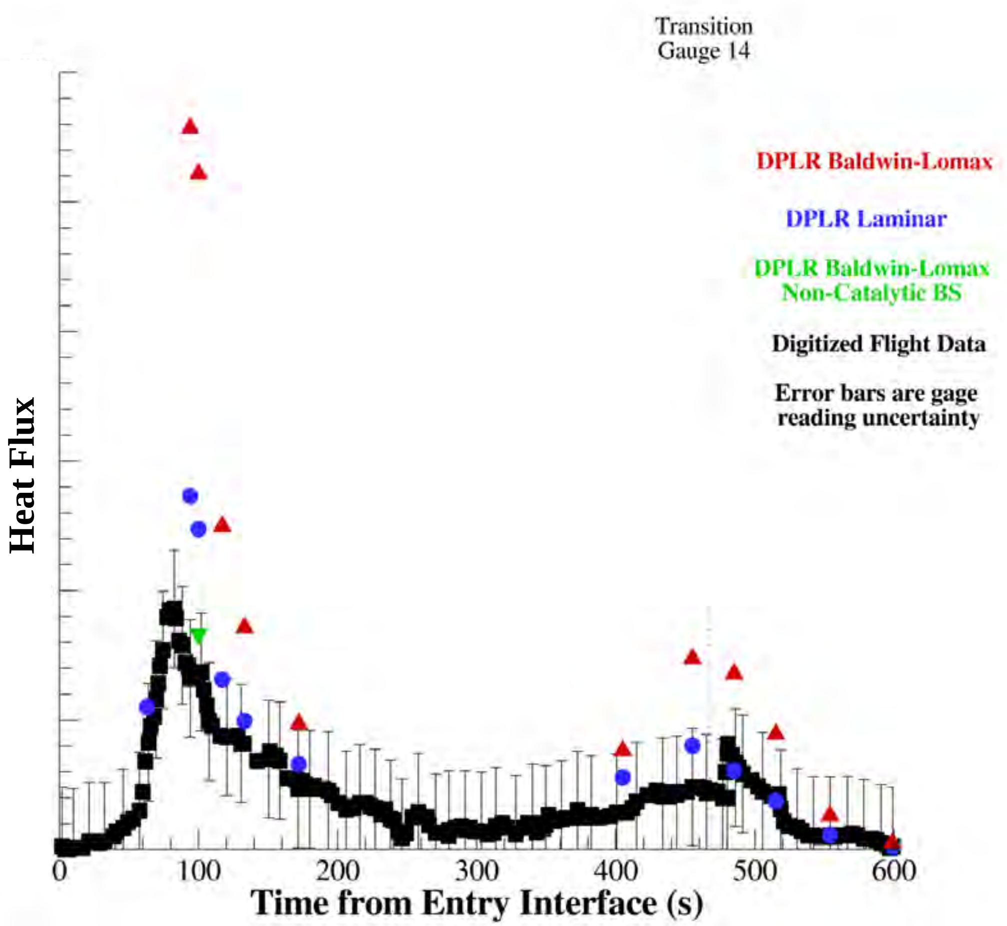


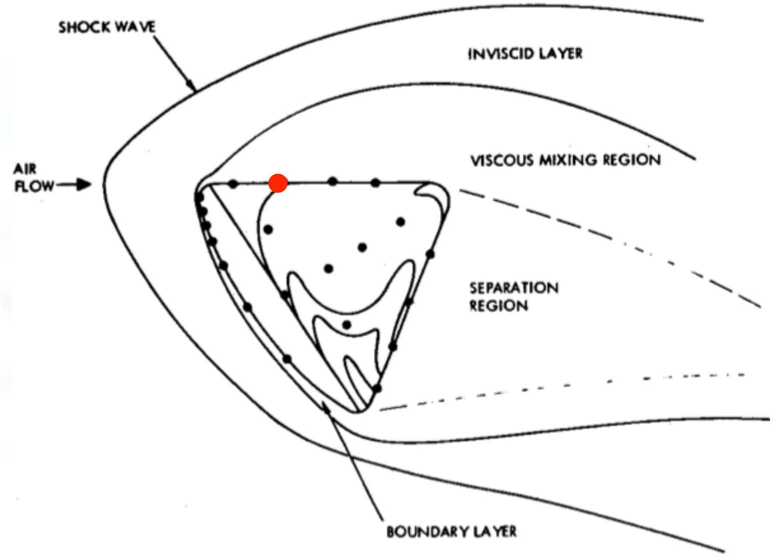


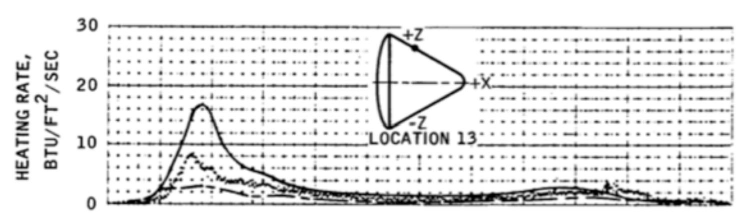
Gauge 13 – Windward Centerline

** Reported data uncertainty is ±2% of the range, which is 100 btu/ft^2/s (so 2 btu/ft^2/s)

$Re_\theta \approx 237$



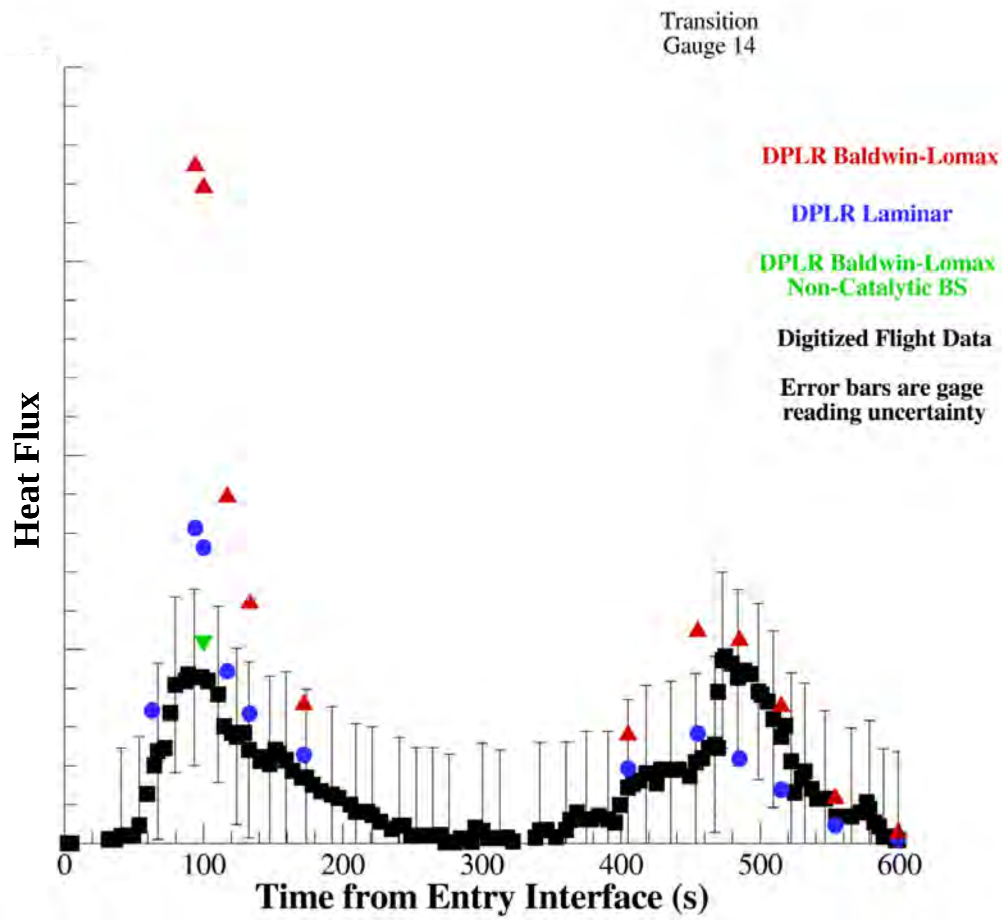


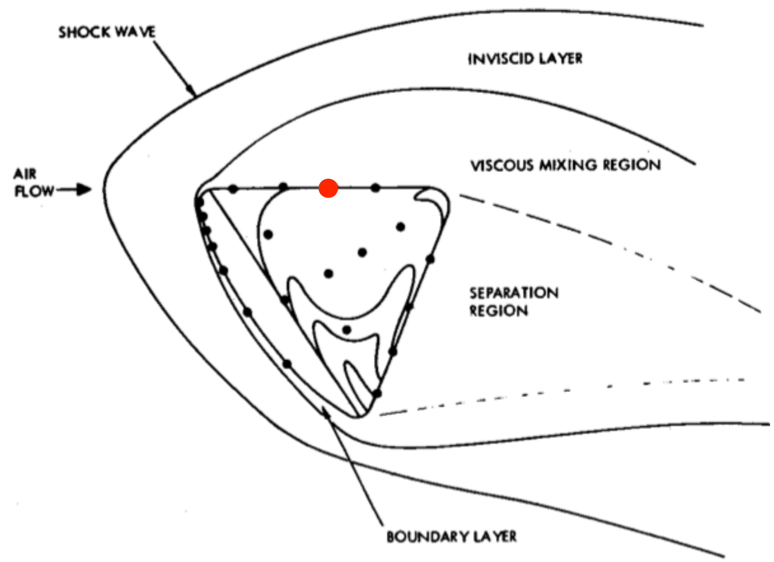


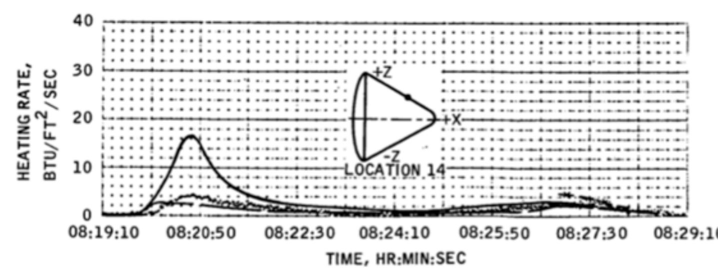
Gauge 14 – Windward Centerline

** Reported data uncertainty is ±2% of the range, which is 100 btu/ft^2/s (so 2 btu/ft^2/s)

$Re_\theta \approx 207$ $Re_\theta \approx 287$

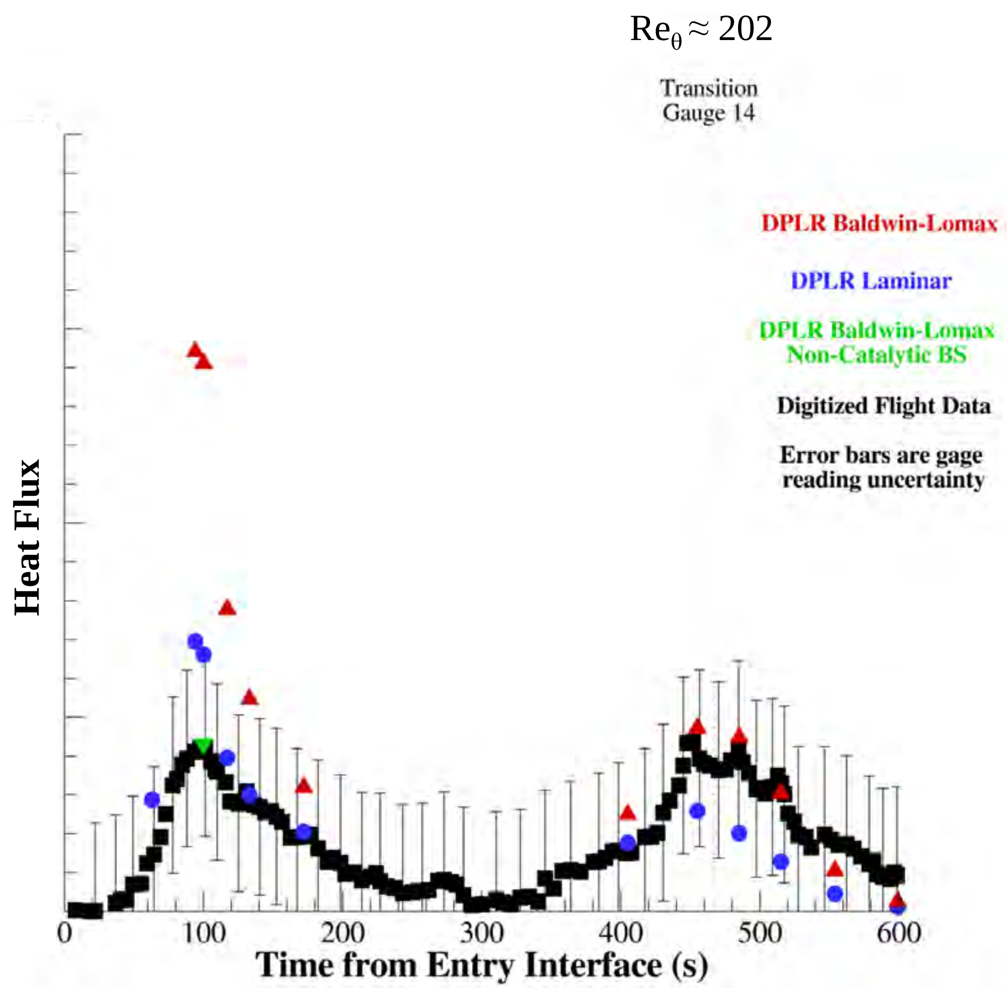


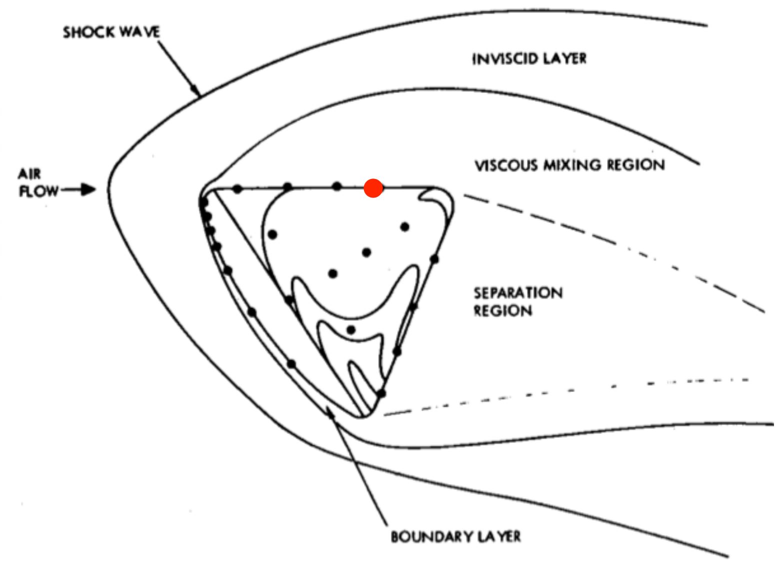


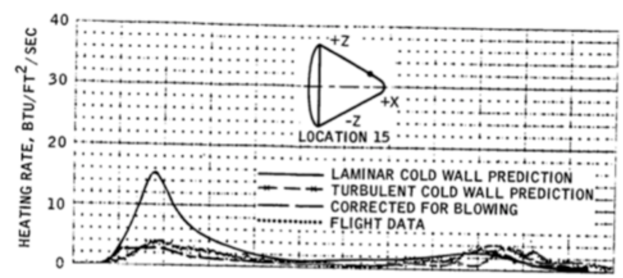


Gauge 15 – Windward Centerline

** Reported data uncertainty is ±2% of the range, which is 100 btu/ft^2/s (so 2 btu/ft^2/s)

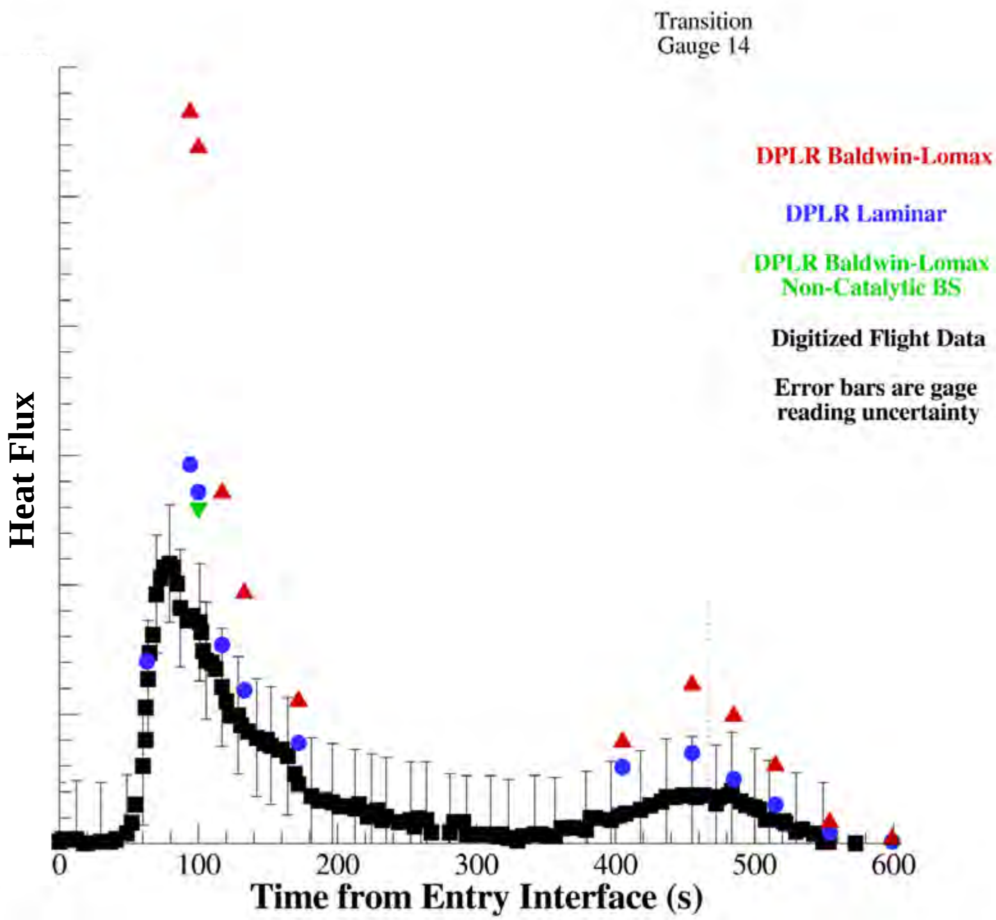


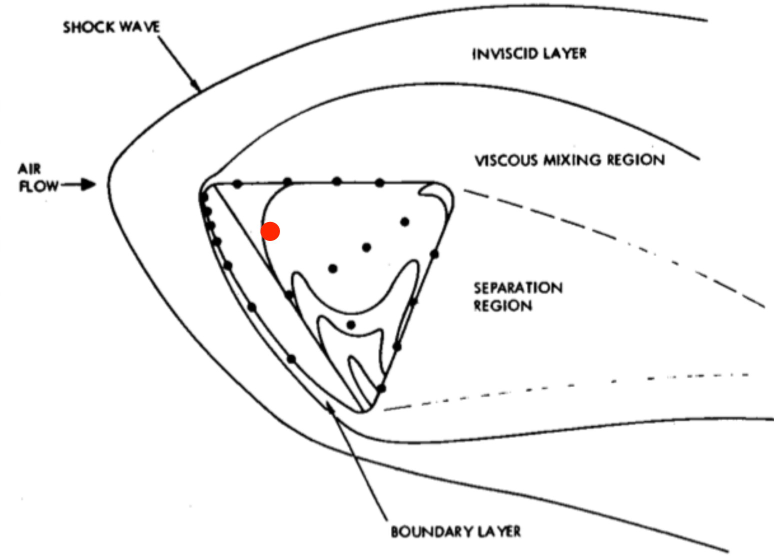


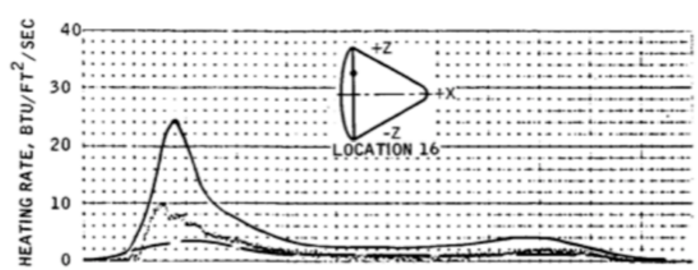


Gauge 16 – Windward Off-Centerline

** Reported data uncertainty is ±2% of the range, which is 100 btu/ft^2/s (so 2 btu/ft^2/s)

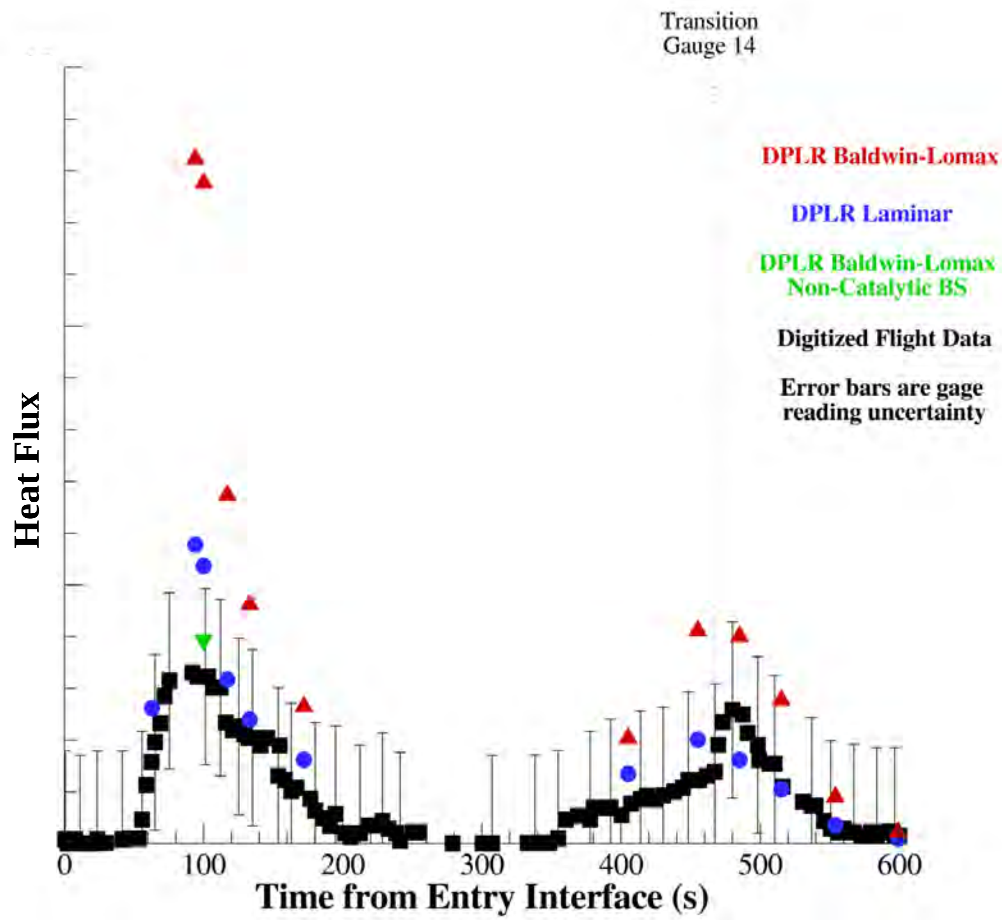


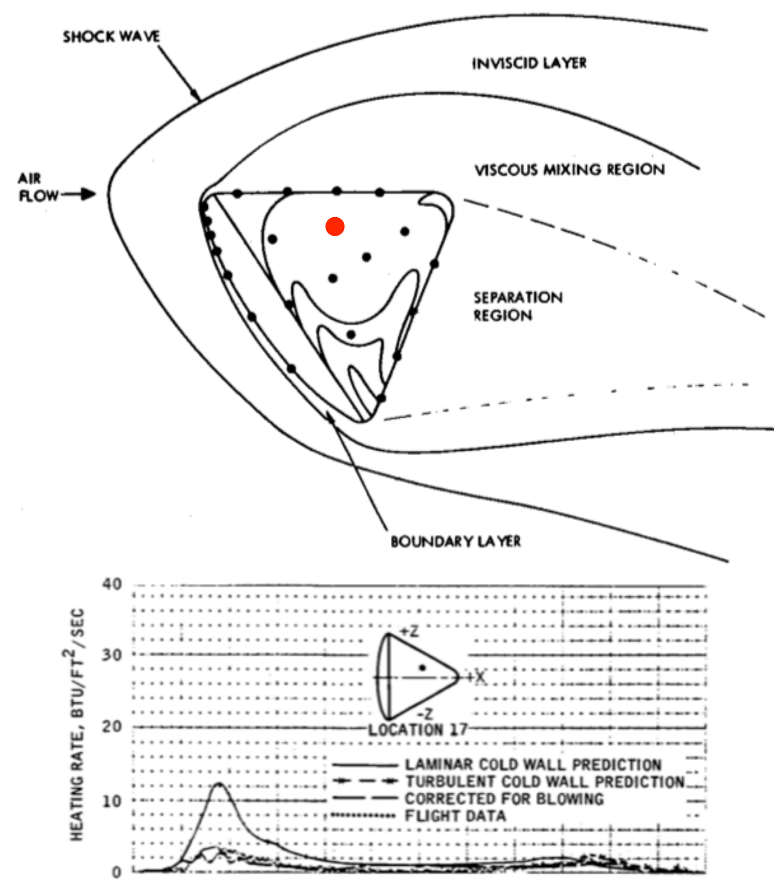




Gauge 17 – Windward Off-Centerline

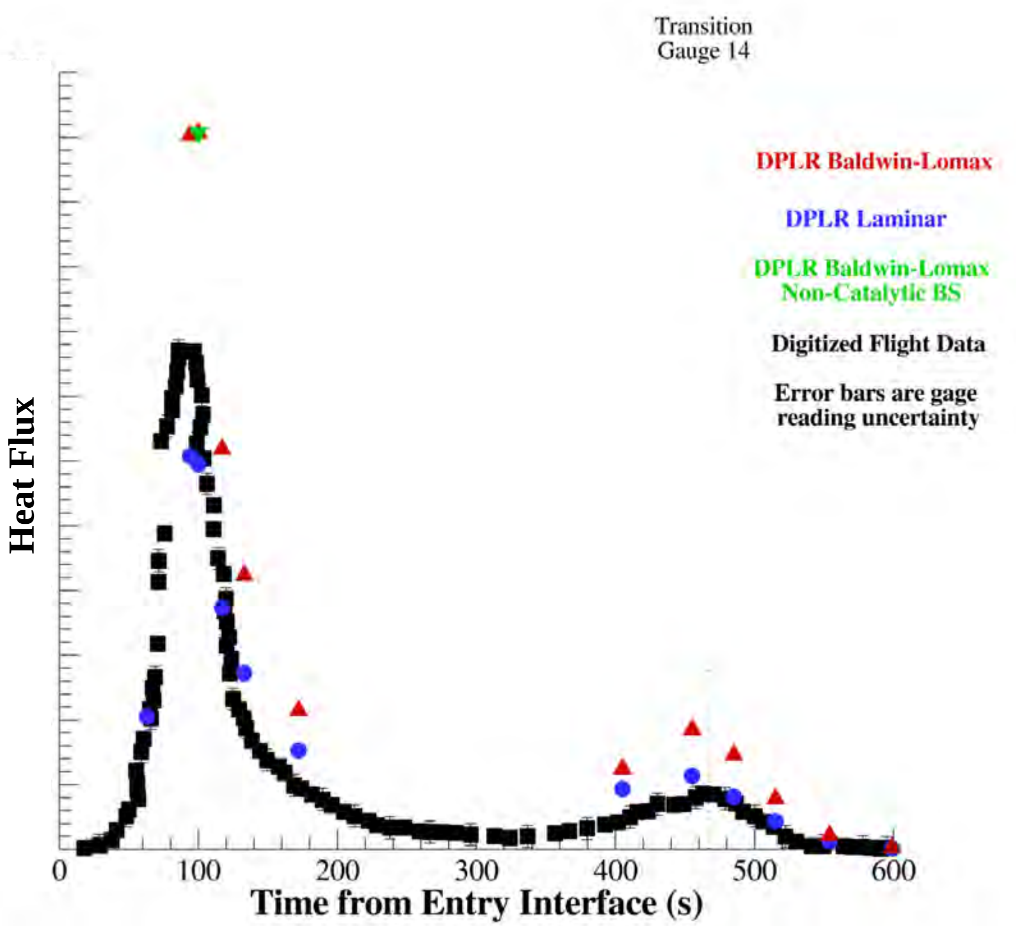
** Reported data uncertainty is ±2% of the range, which is 75 btu/ft^2/s (so 1.5 btu/ft^2/s)

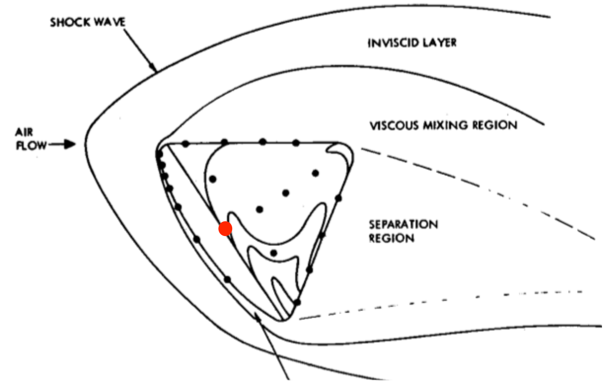




Gauge 18 – Shoulder

** Reported data uncertainty is ±2% of the range, which is 75 btu/ft^2/s (so 1.5 btu/ft^2/s)





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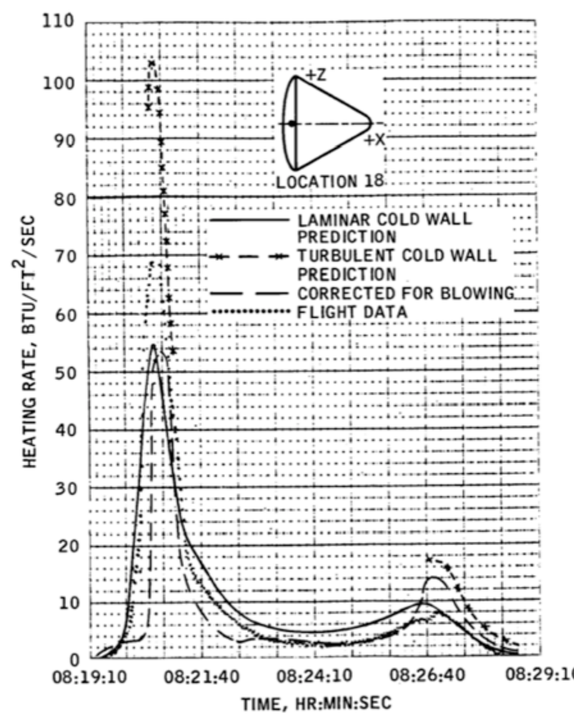
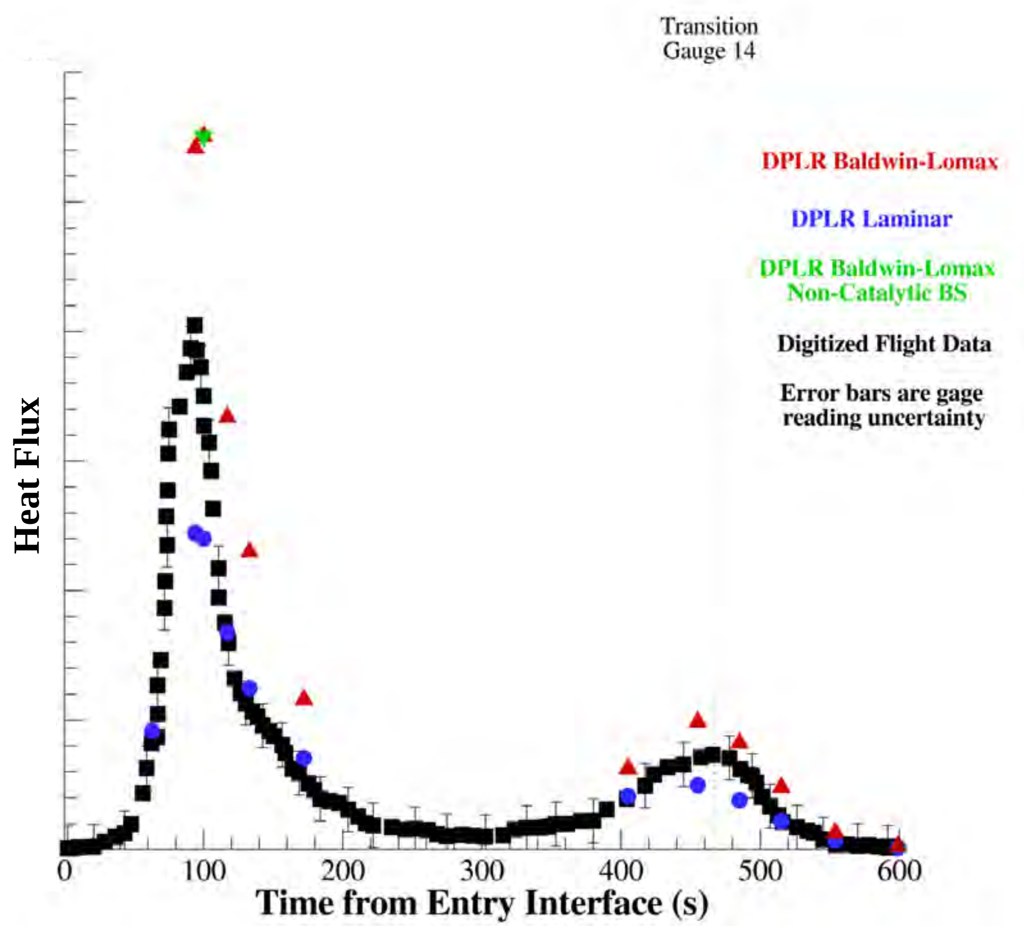
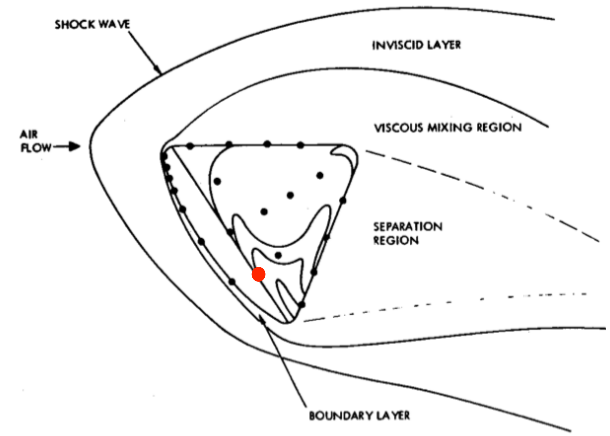
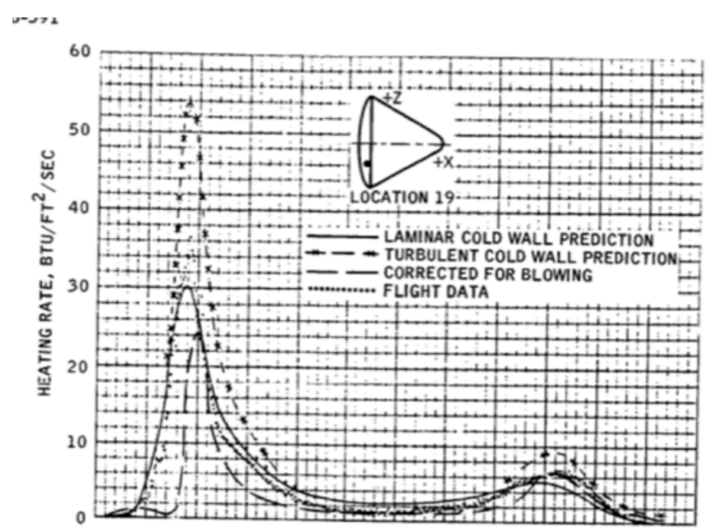


Gauge 19 – Shoulder

** Reported data uncertainty is ±2% of the range, which is 75 btu/ft^2/s (so 1.5 btu/ft^2/s)

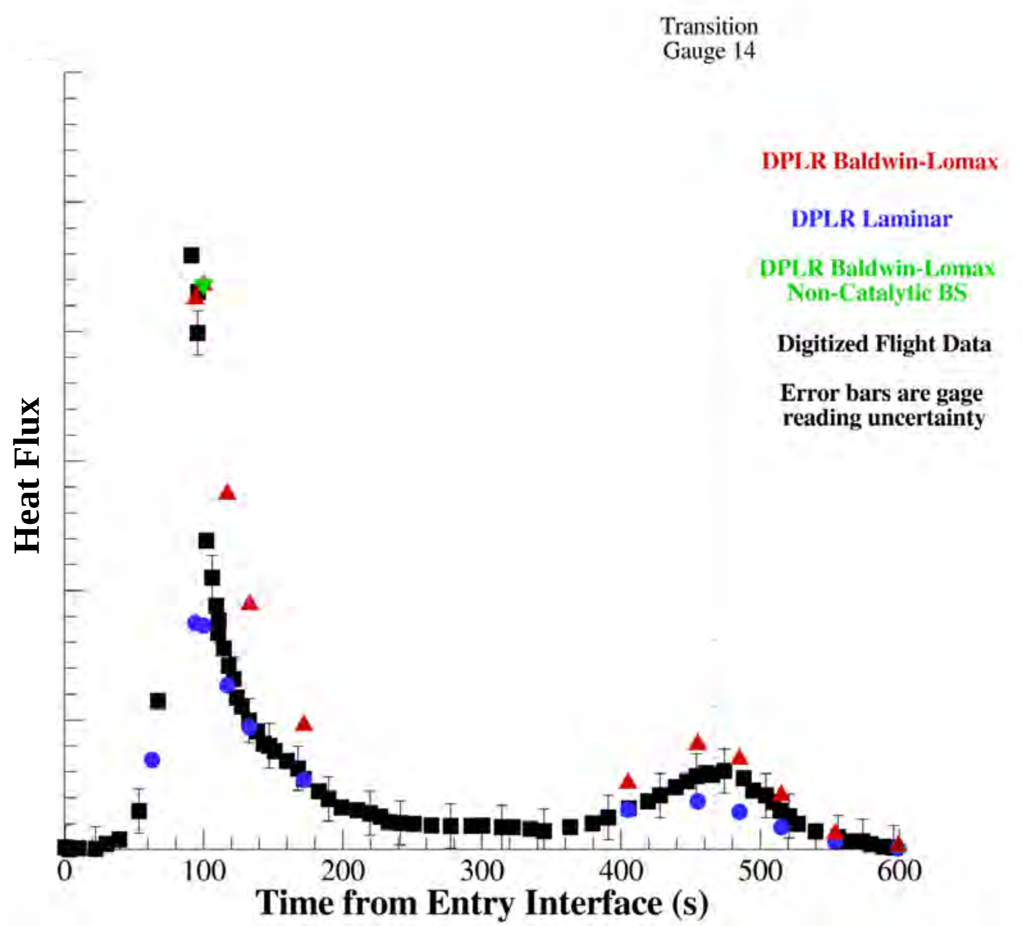


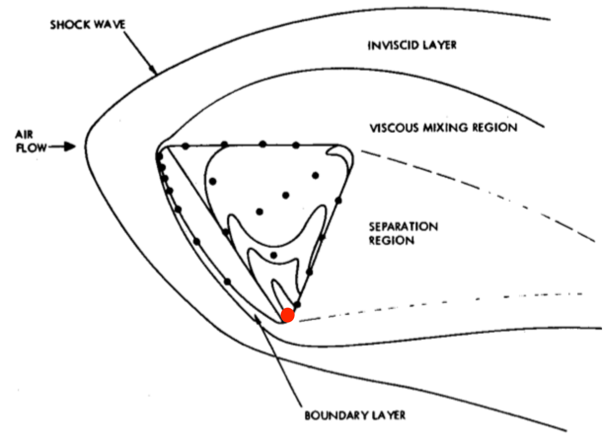


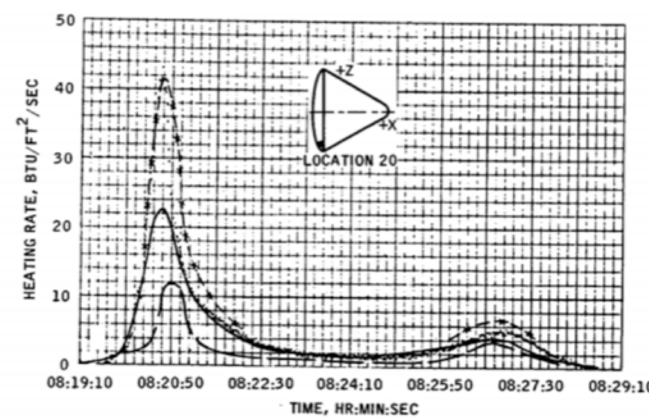


Gauge 20 – Shoulder

** Reported data uncertainty is ±2% of the range, which is 75 btu/ft^2/s (so 1.5 btu/ft^2/s)



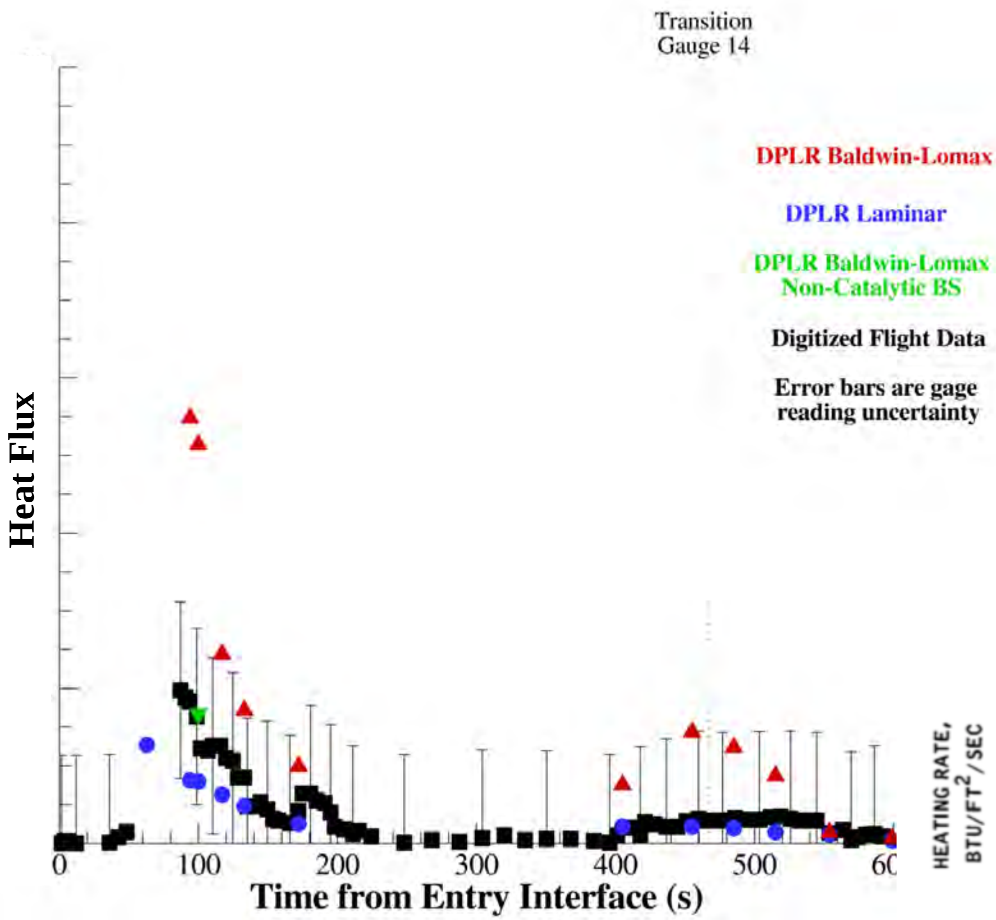


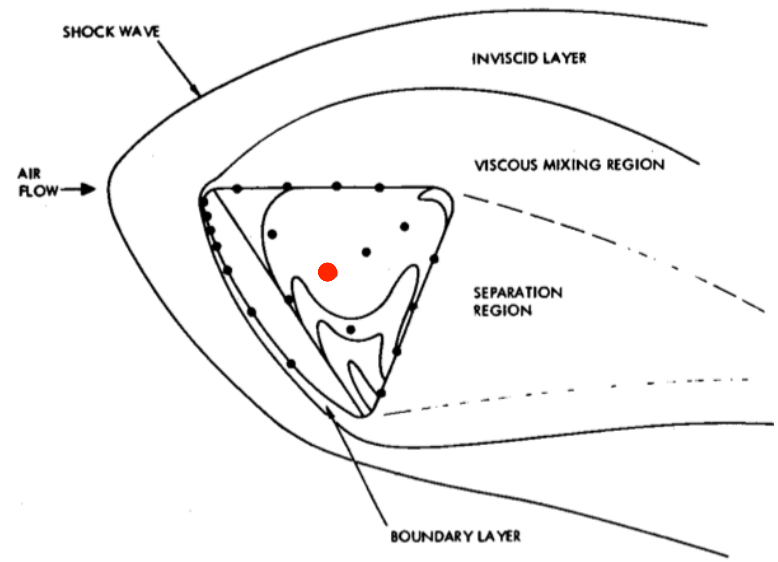


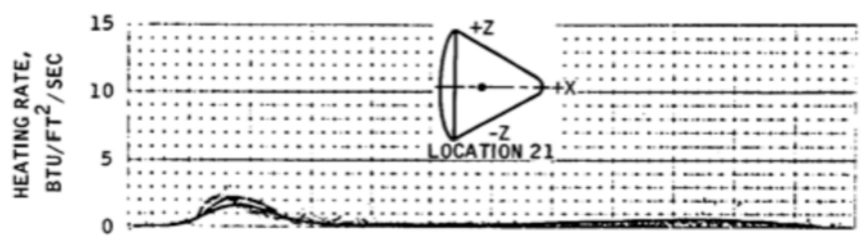
(D) LOCATIONS 19 AND 20.

Gauge 21 – Leeward –y-axis

** Reported data uncertainty is ±2% of the range, which is 50 btu/ft²/s (so 1 btu/ft²/s)

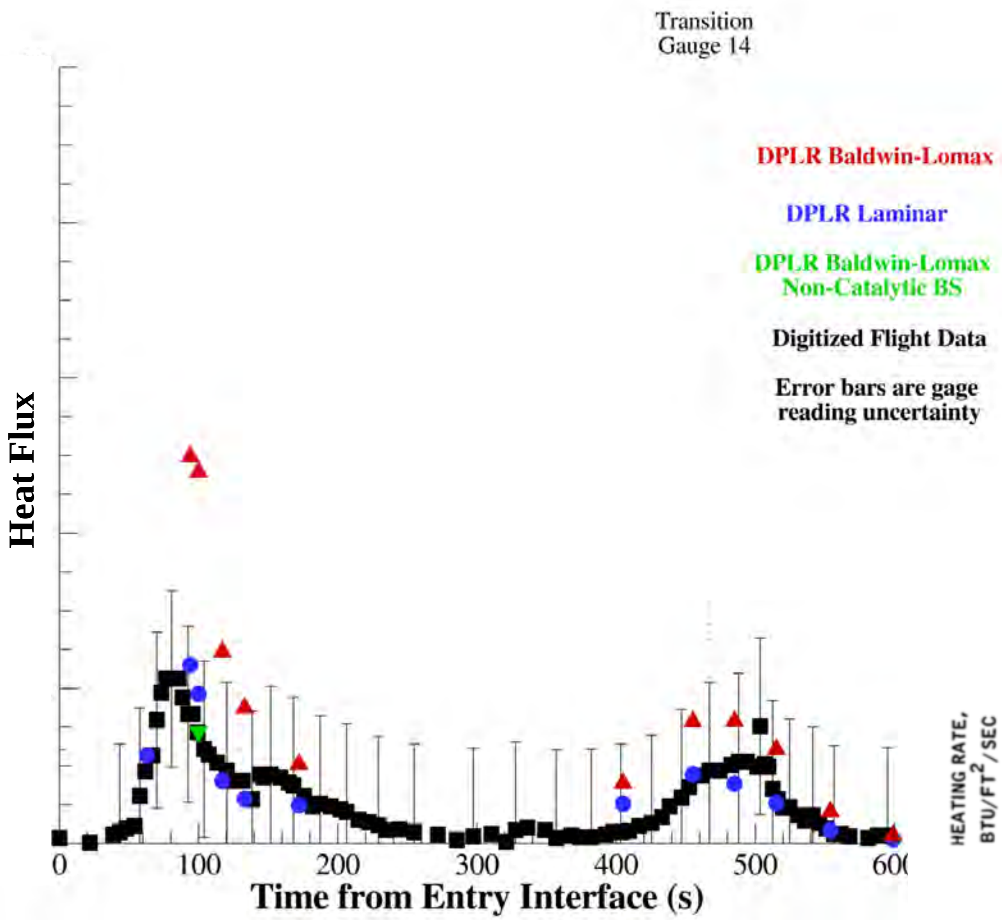


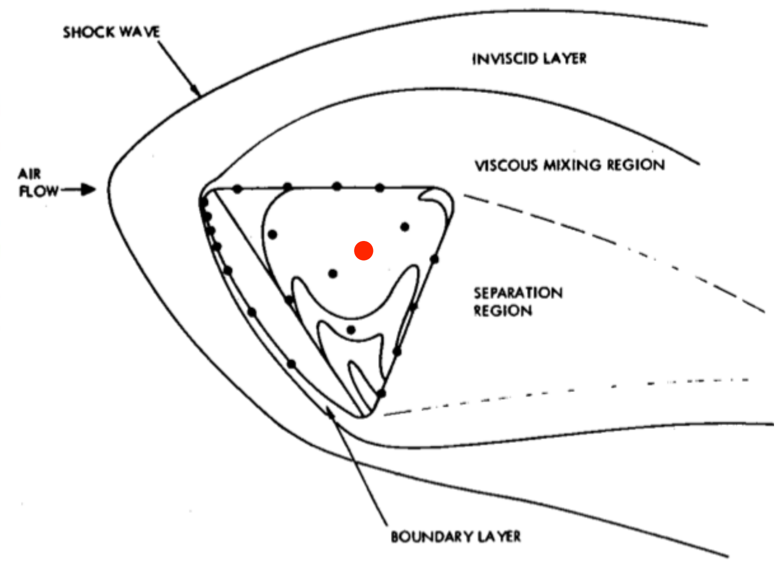


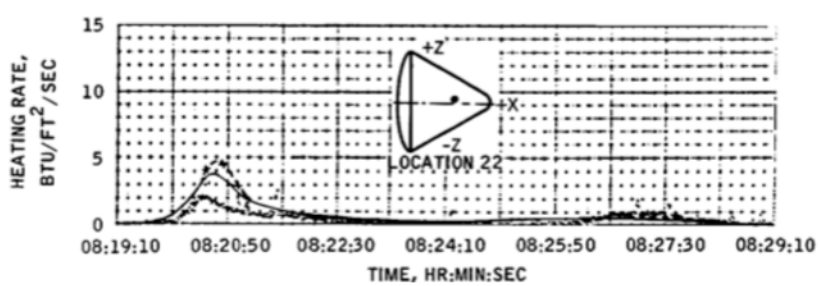


Gauge 22 – Leeward –y-axis

** Reported data uncertainty is ±2% of the range, which is 50 btu/ft²/s (so 1 btu/ft²/s)

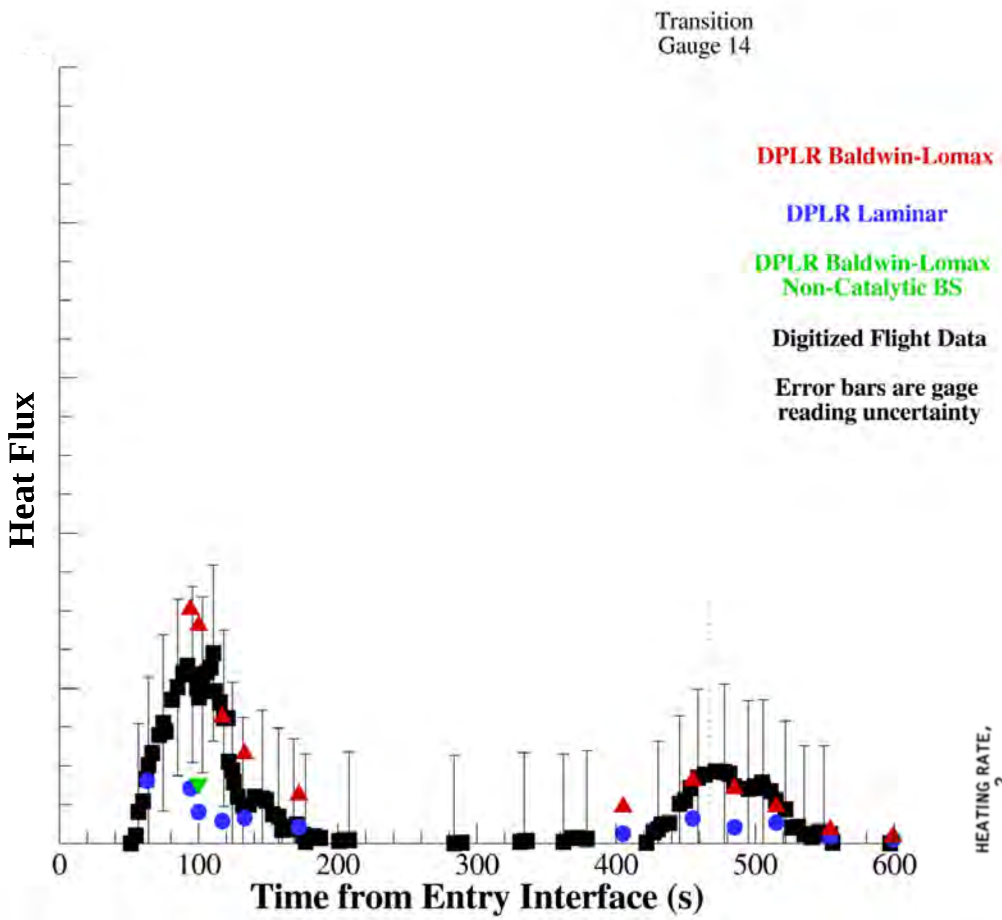


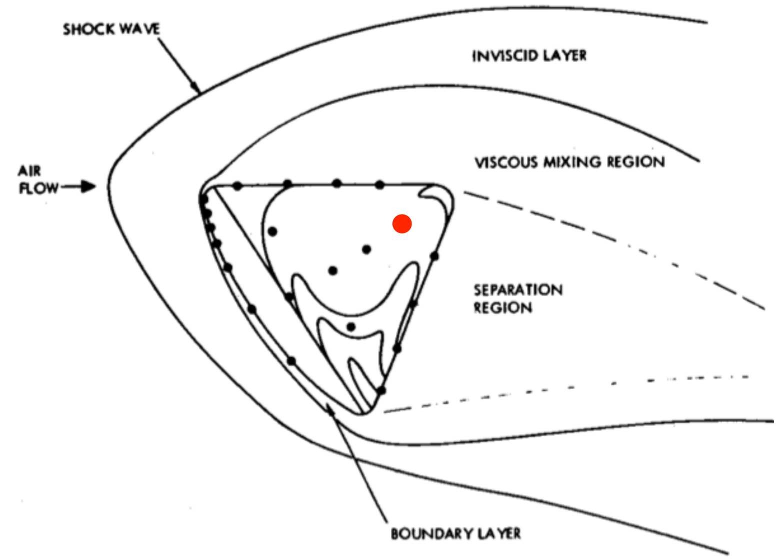


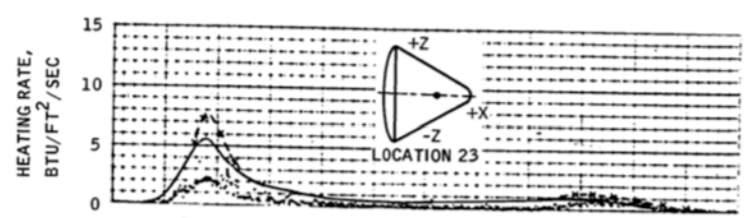


Gauge 23 – Leeward –y-axis

** Reported data uncertainty is ±2% of the range, which is 50 btu/ft^2/s (so 1 btu/ft^2/s)

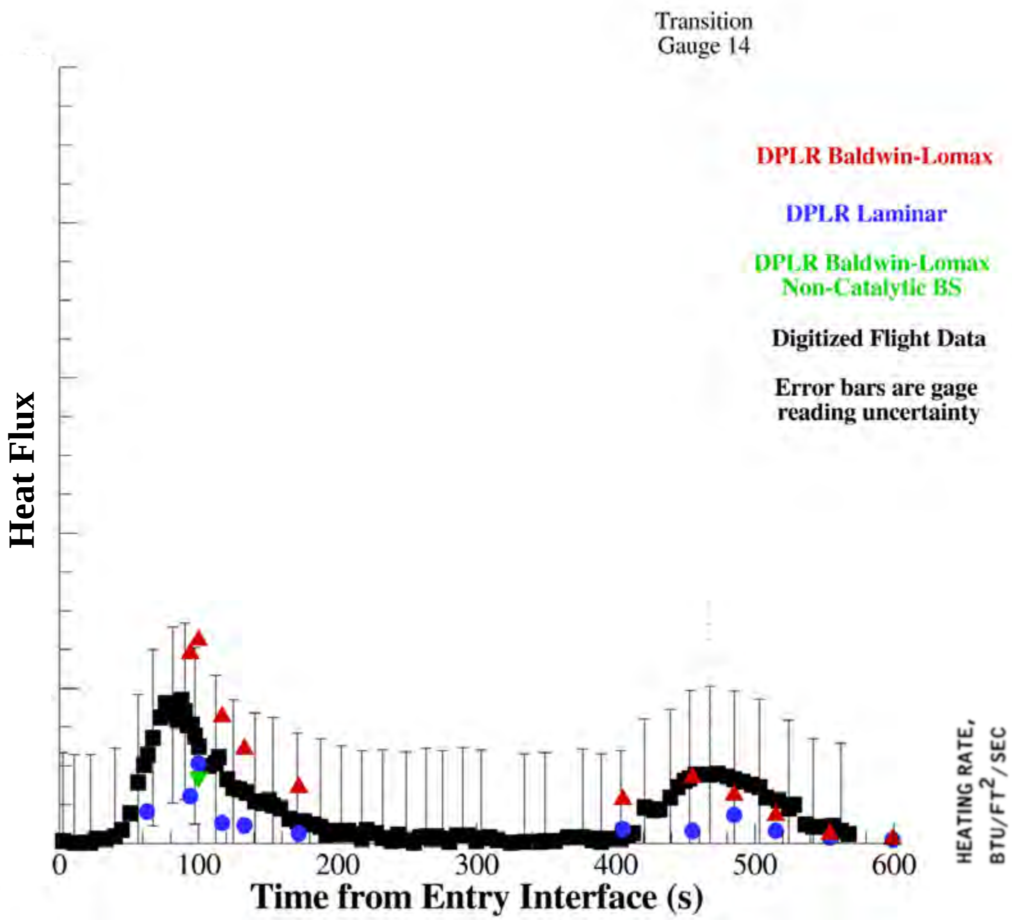


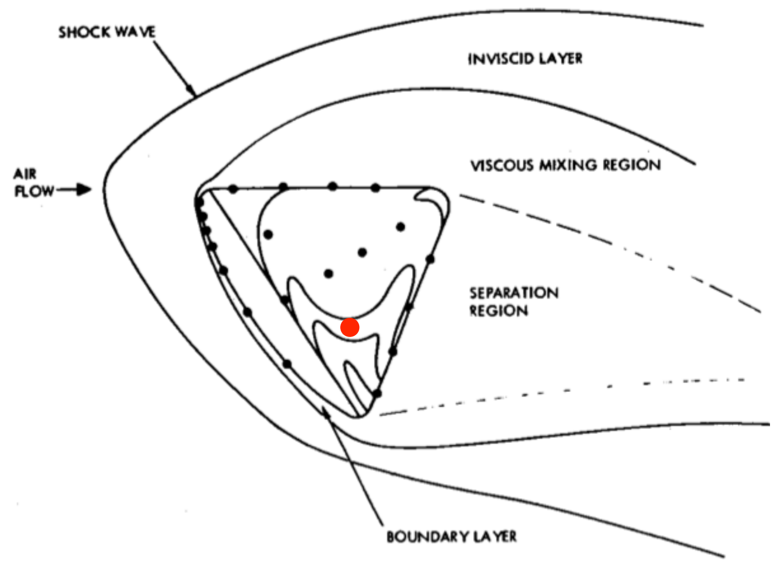


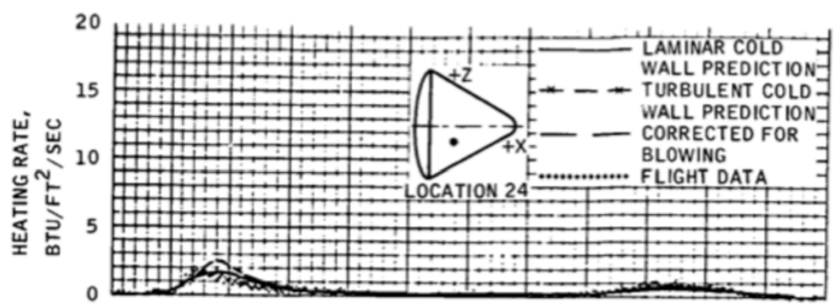


Gauge 24 – Leeward Off-Centerline

** Reported data uncertainty is ±2% of the range, which is 50 btu/ft^2/s (so 1 btu/ft^2/s)

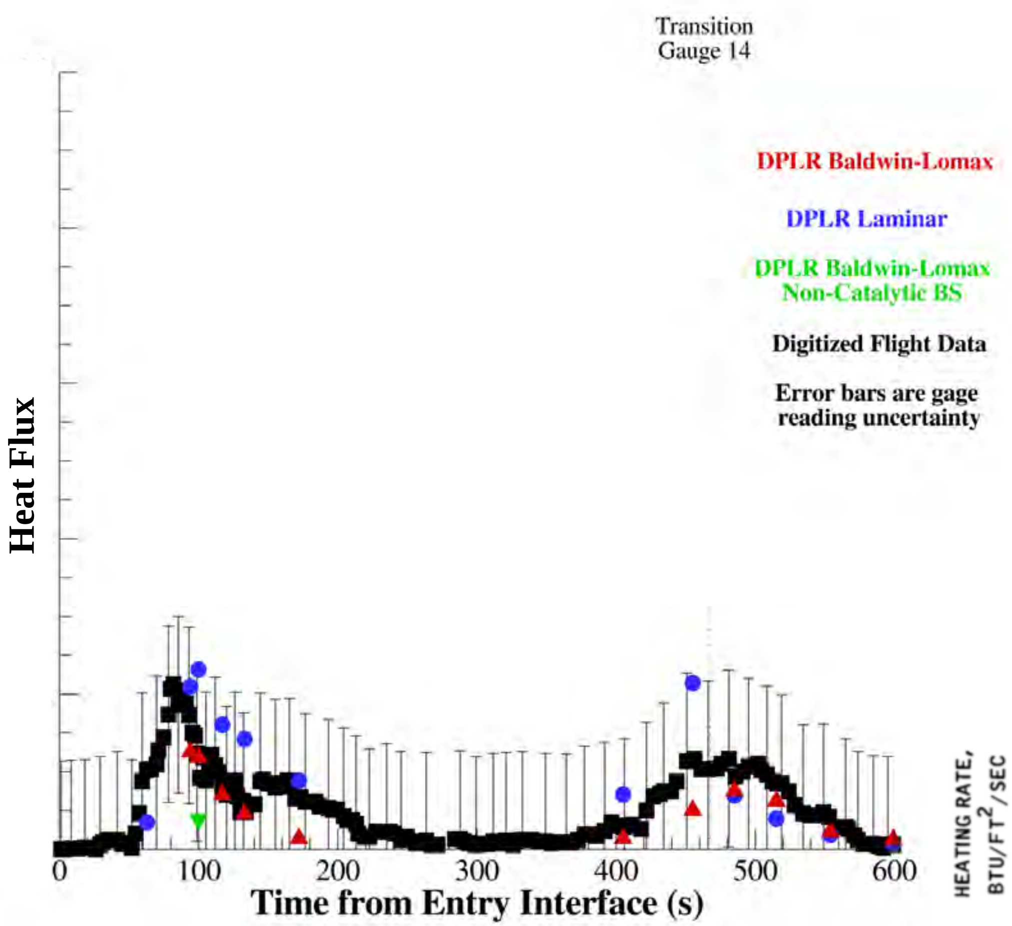


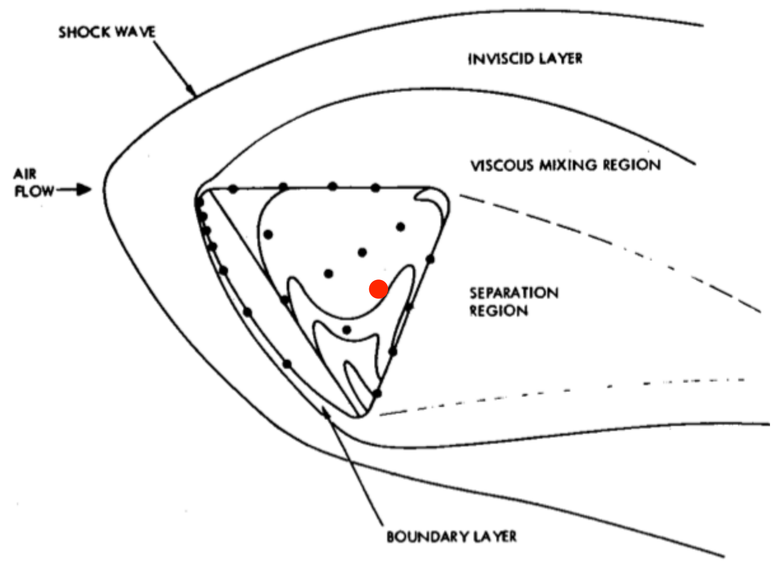


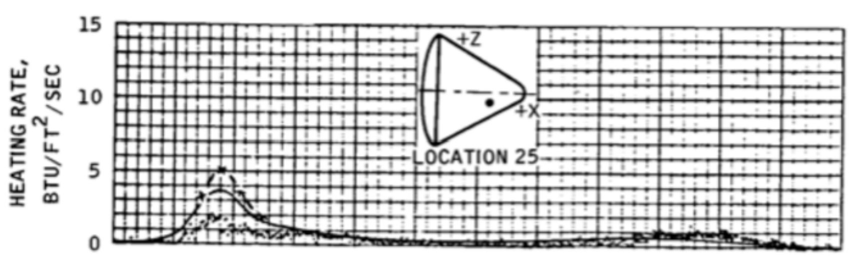


Gauge 25 – Leeward Off-Centerline

** Reported data uncertainty is ±2% of the range, which is 50 btu/ft^2/s (so 1 btu/ft^2/s)

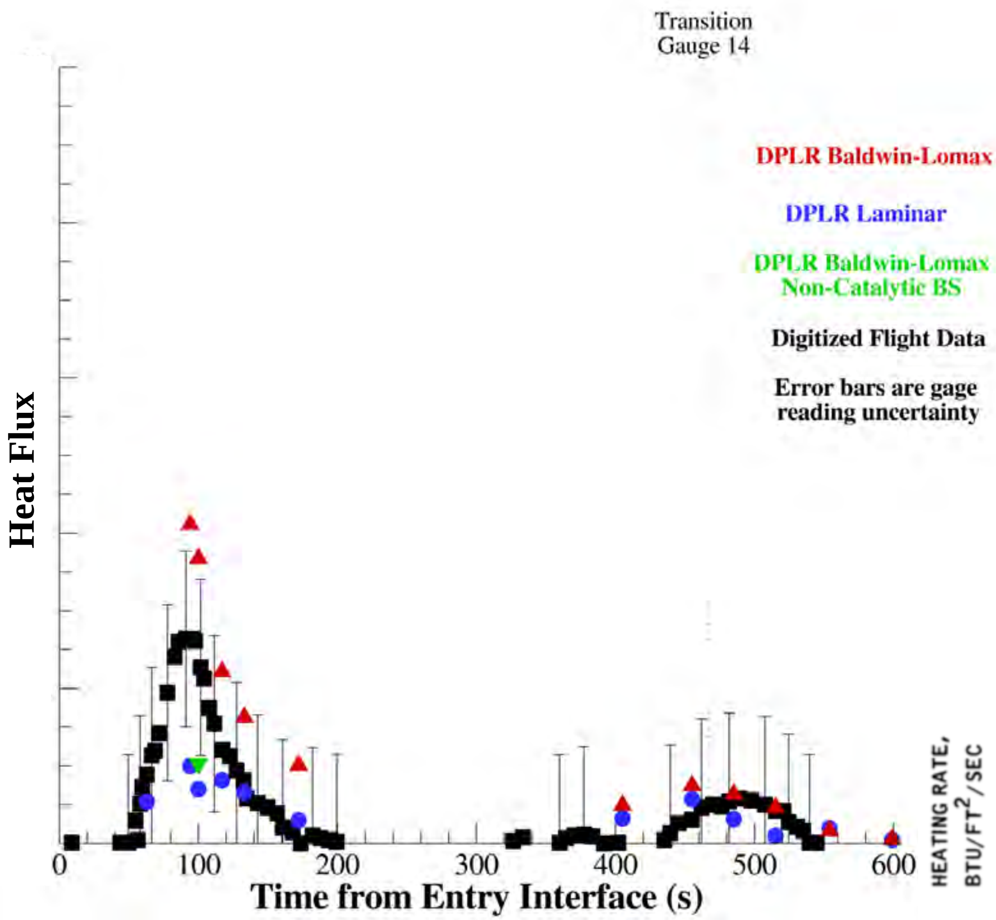


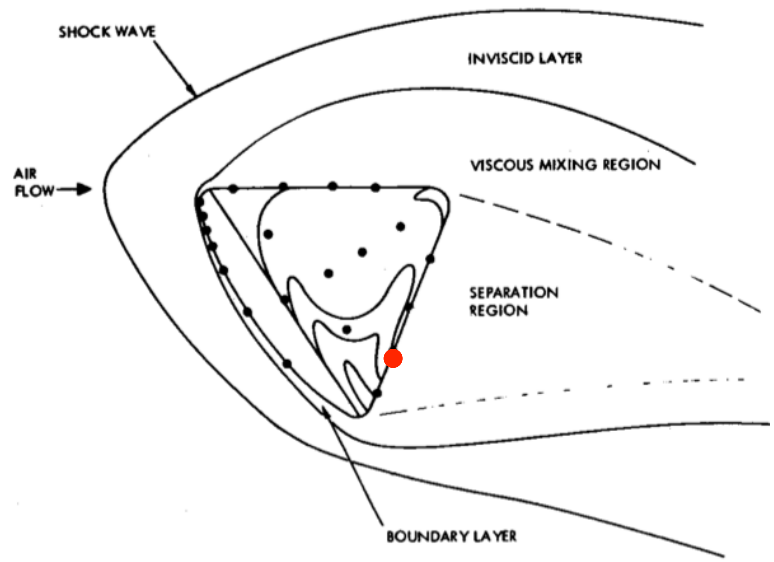


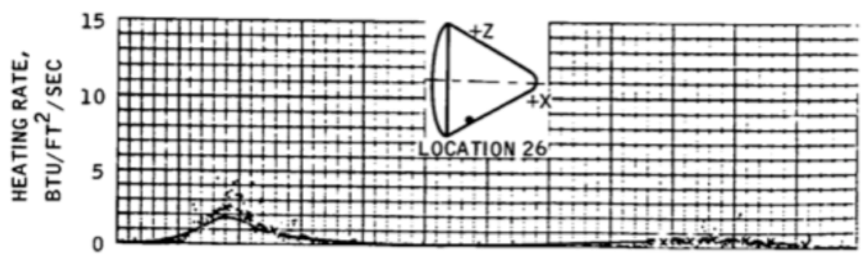


Gauge 26 – Leeward Centerline

** Reported data uncertainty is ±2% of the range, which is 50 btu/ft^2/s (so 1 btu/ft^2/s)

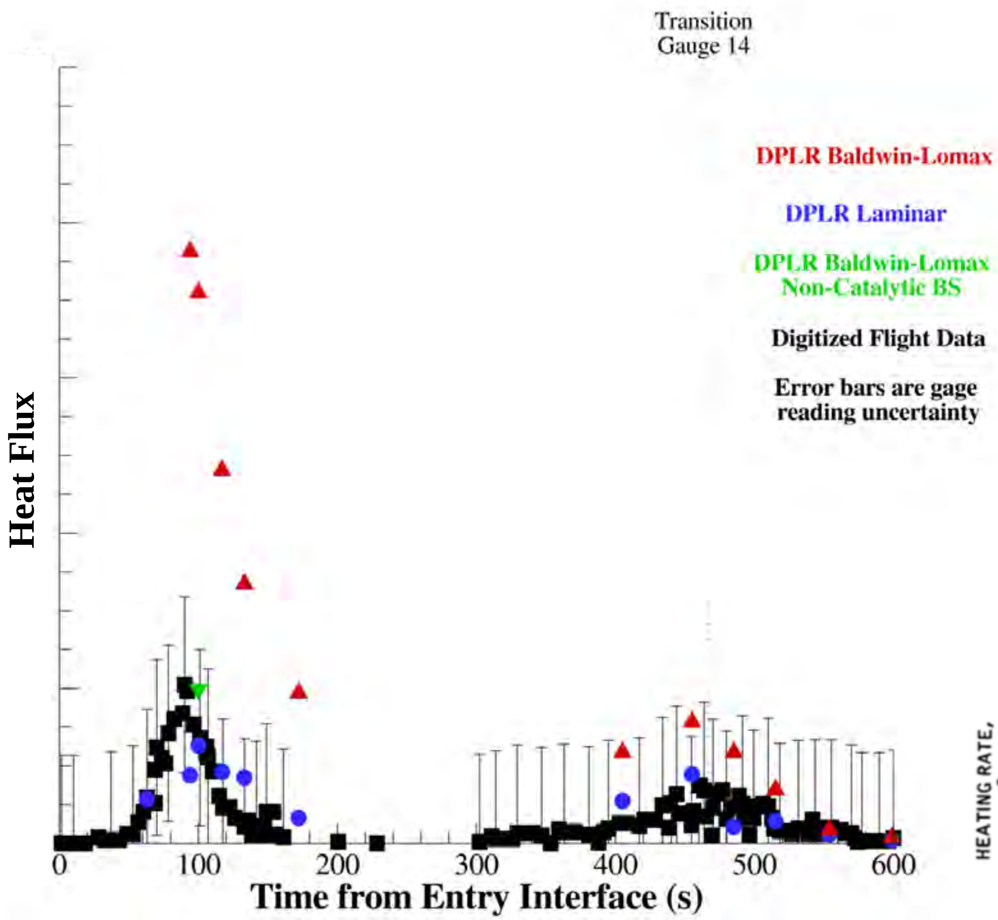


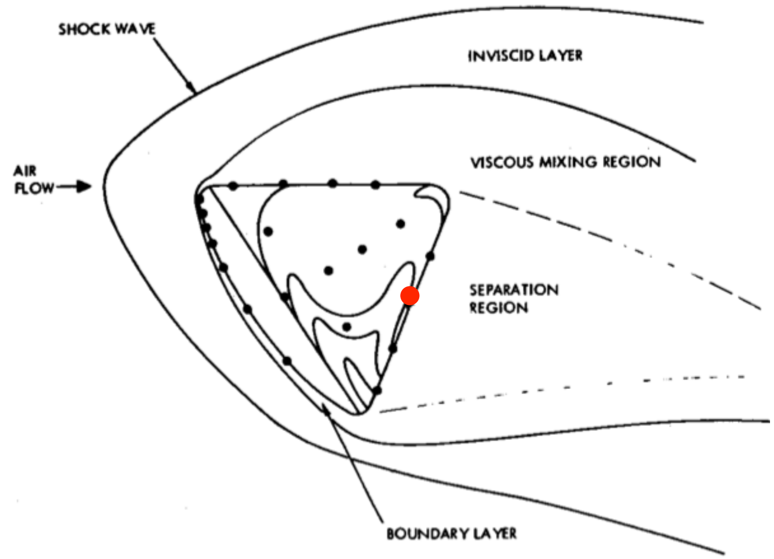


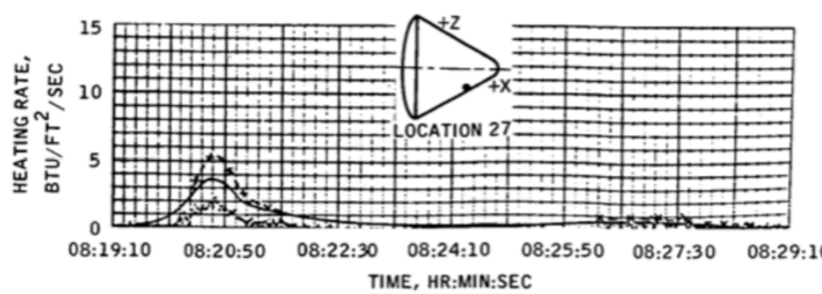


Gauge 27 – Leeward Centerline

** Reported data uncertainty is ±2% of the range, which is 50 btu/ft^2/s (so 1 btu/ft^2/s)

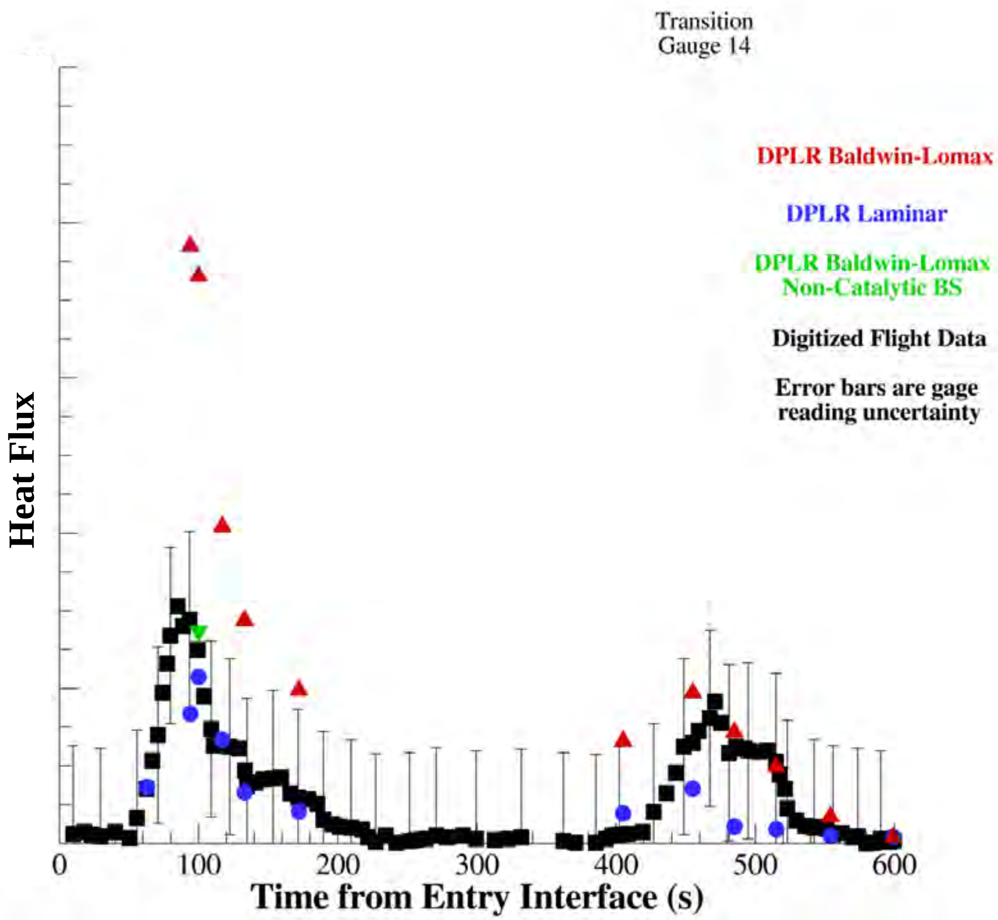


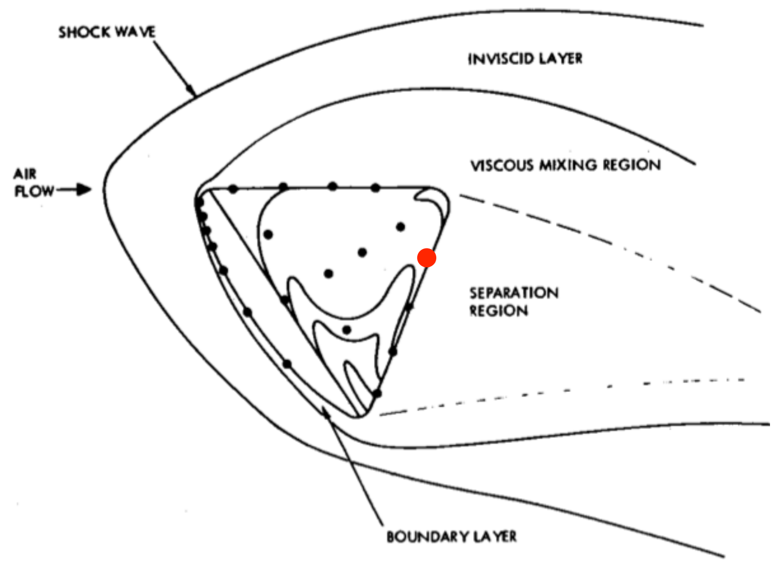


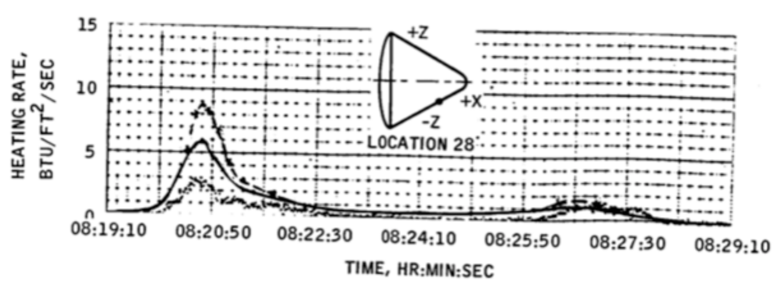


Gauge 28 – Leeward Centerline

** Reported data uncertainty is ±2% of the range, which is 50 btu/ft²/s (so 1 btu/ft²/s)







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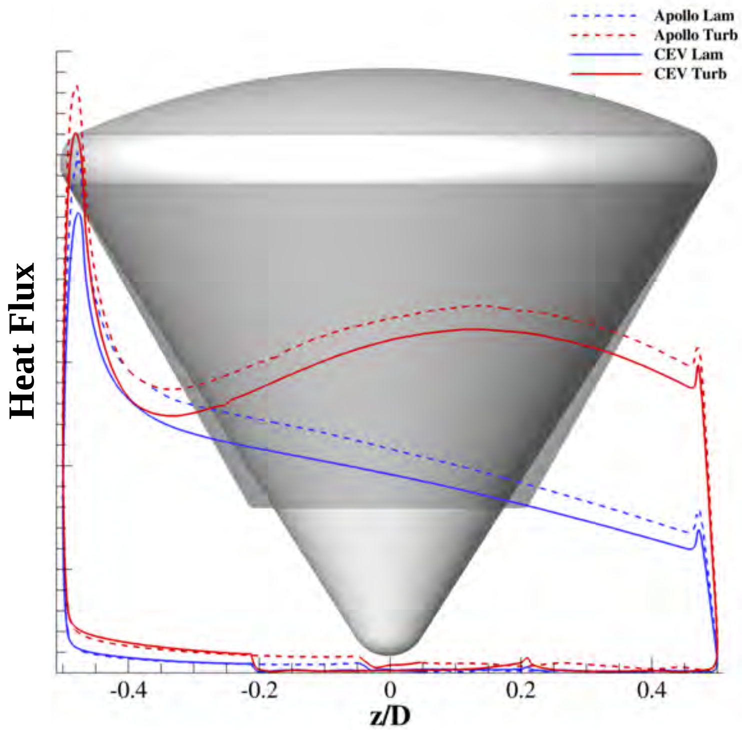
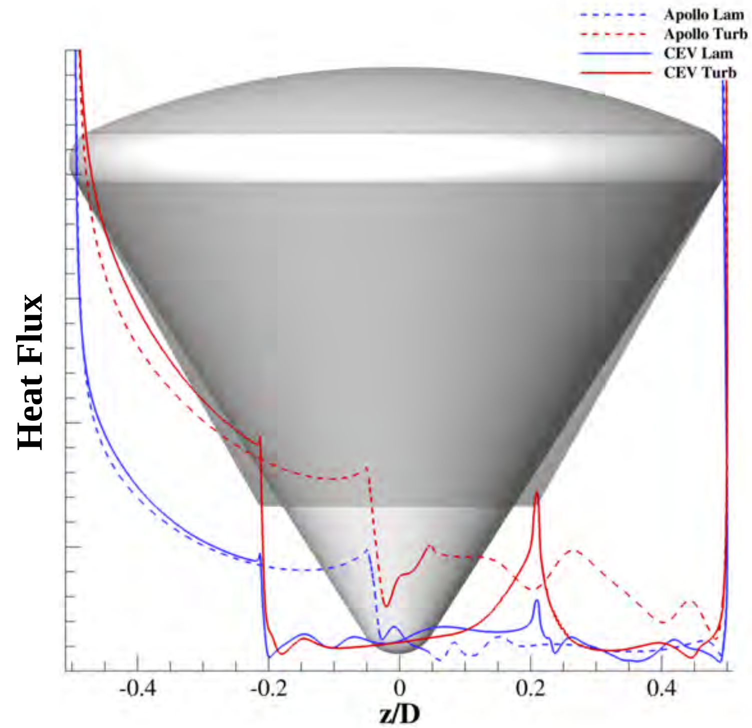
Which is Hotter?? Orion or Apollo?

Heatshield – heating scales as $1/\sqrt{r}$, so Apollo has higher heat fluxes

Windward Backshell – Orion has higher heat fluxes due to the larger backshell angle

Separated Backshell – Variable





Conclusions

Windward Gauges (12-17) – Apollo IV Flight Data compare extremely well with DPLR laminar predictions when the flow is laminar, and also well to DPLR Baldwin-Lomax turbulent predictions when the flow is turbulent. At peak heating, the turbulent non-catalytic backshell solution matches very well.

Shoulder Gauges (18-20) – Apollo IV Flight Data is over predicted by DPLR Baldwin-Lomax solutions and matches fairly well with the laminar predictions.

Separation Line Gauges (21-22) – Apollo IV Flight Data matches the laminar predictions later on, the turbulent full-catalytic over-predicts, and the turbulent non-catalytic matches at peak heating.

Separated Gauges –

23-24: Flight Data matches the turbulent predictions, and laminar under-predicts the flight data.

25: The laminar predictions are greater than the turbulent predictions for this area, and the flight data are somewhere in-between, but fairly close to the laminar levels.

26-28: (Centerline) The DPLR laminar predictions are very close to the flight data, with the turbulent over-predicting. After transition, the turbulent matches very well with the flight data.

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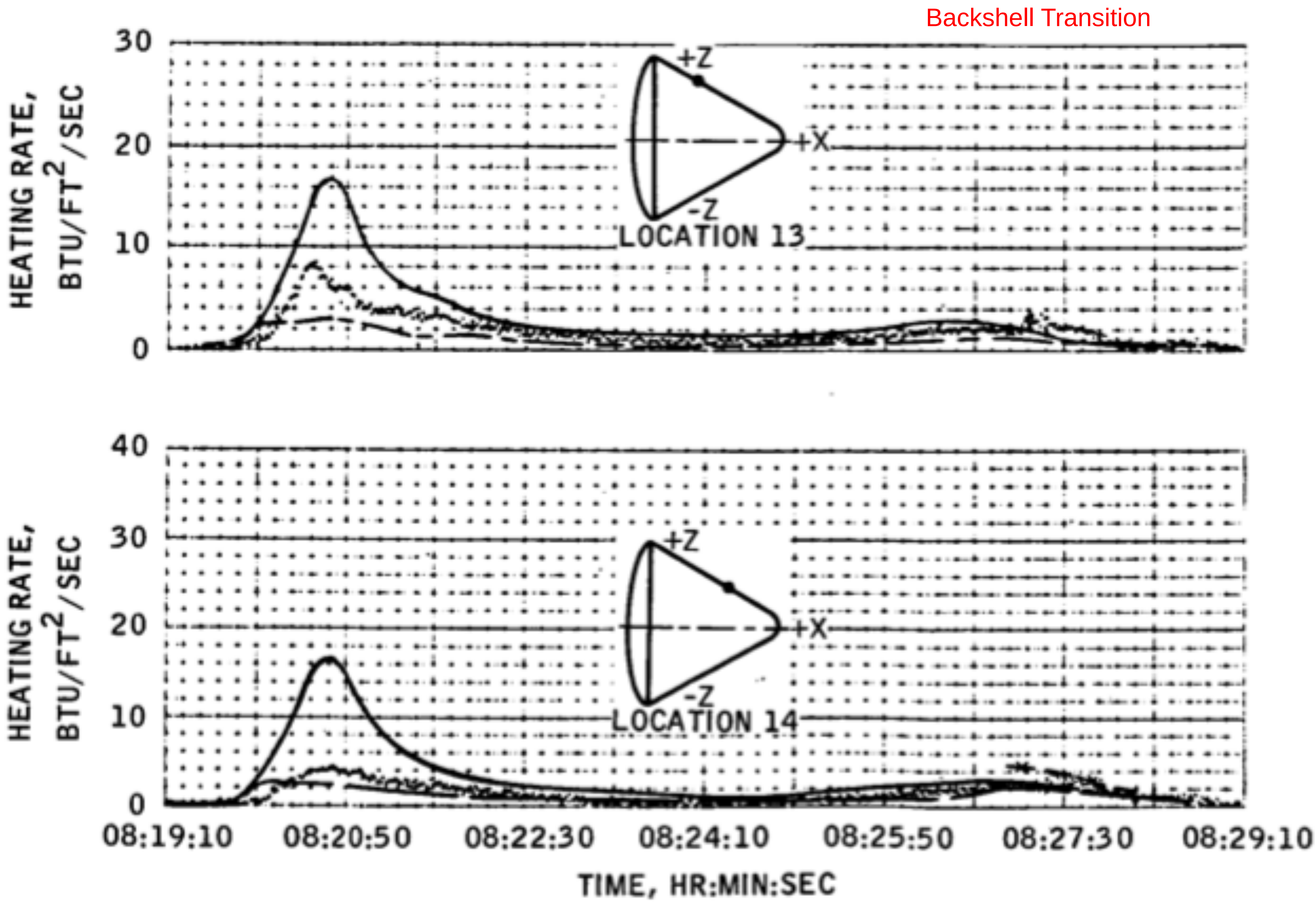
Back Up

Time Traces of Transition – Apollo IV Data



Apollo IV Instrumentation Types and Layout

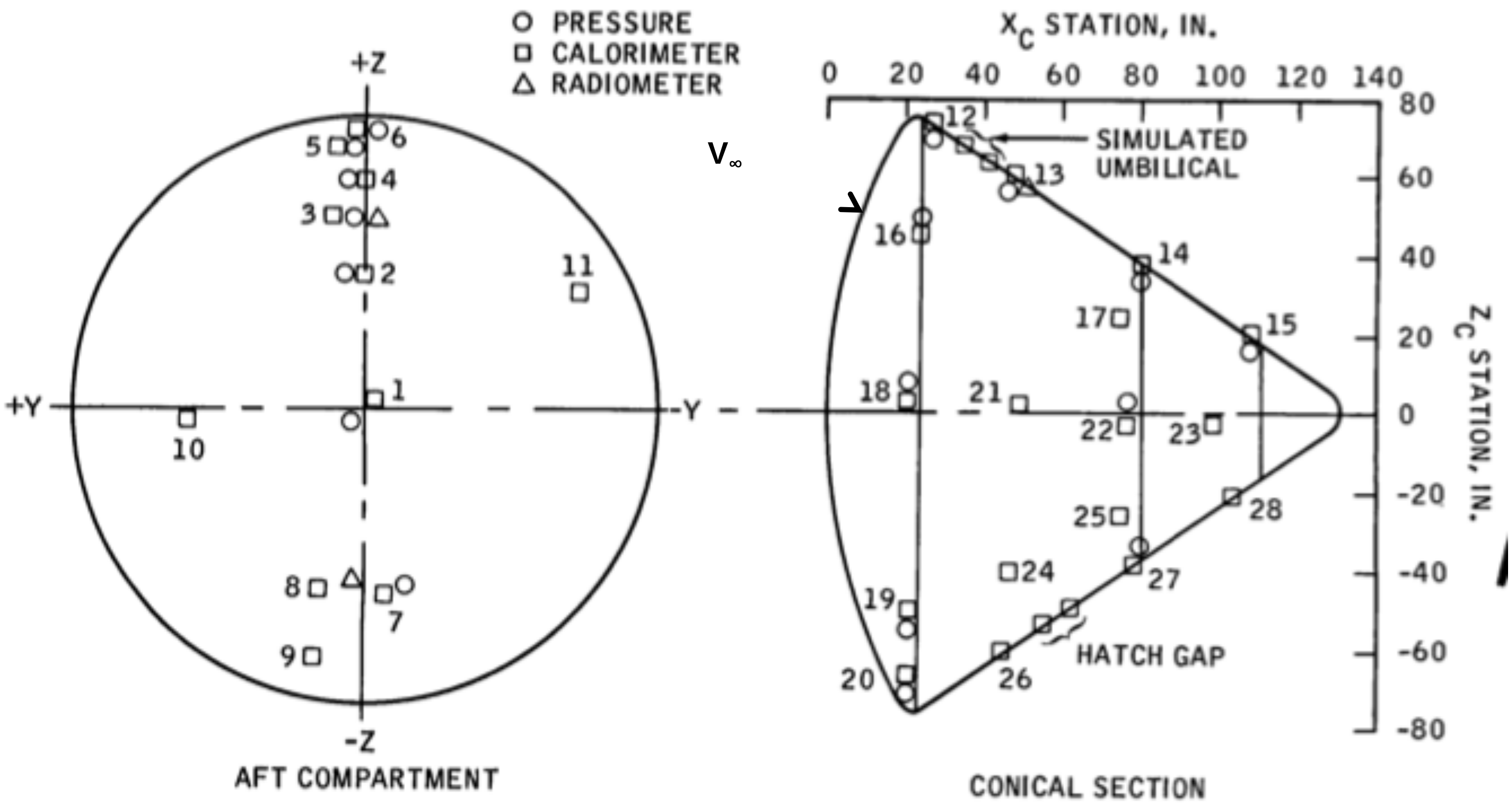


FIGURE 5.4-1.- SKETCH OF APOLLO COMMAND MODULE SHOWING LOCATIONS OF AEROTHERMODYNAMIC SENSORS.

Gage Locations

	Preflight Location		Postflight Location	
	r	theta	r	theta
12	26.5	93	26.5	93.72
13	50	85	50	85.32
14	83.4	82	83.38	82.62
15	104	101	104	101.48
16	26.3	138	26.33	137.93
17	78.9	137	78.88	137.07
18	18.2	179	18.2	179.42
19	18.5	225	18.5	225
20	18.5	264	18.2	269.98
21	52.5	179	52.5	178.98
22	78.9	189	78.88	189.02
23	104	191	104	191.48
24	50	229	50	226.85
25	78.9	226	78.88	226.17
26	50	272	50	271.97
27	78.9	268	78.88	267.83
28	104	275	104	274.83

Sample Separated Region Time Traces

Reported uncertainty is ±2% of the range, which for these gauges is 50 btu/ft^2/s (so 1 btu/ft^2/s)