Overview of Post-Flight Analysis of the Stardust Sample Return Capsule Earth Entry

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IPPW-5, Bordeaux, France, June 2007

POC: Dean Kontinos, 650-604-4283

Stardust Sample Return

Stardust Post-flight Analysis

Presenting Work of Many

- Project Management

  James Reuther - Crew Exploration Vehicle Thermal Protection System Advanced Development Project Manager (ARC)

  Dean Kontinos - Stardust task lead (NESC-ARC)

- Materials Analysis

  Chris Dobell - laser scan (ARC)

  Miria Finckenor - surface reflectivity (MSFC)

  Joseph Lavelle - laser scan (ARC)

  Karen McNamara - Curator (JSC)

  Frank Milos - material response modeler (ARC)

  Betsy Pugel - UV material scan (GSFC)

  Jerry Ridge - emittance testing (ARC)

  Stefan Schuet - laser scan (ARC)

  Steve Sepka - material response modeler (ARC)

  Maegan Spencer - mass spectrometry (Stanford)

  Mairead Stackpoole - materials lead (ARC)

  Matt Switzer - material process lead (ARC)

  Jeff Verson - laser scan (ARC)

Presenting Work of Many (cont)

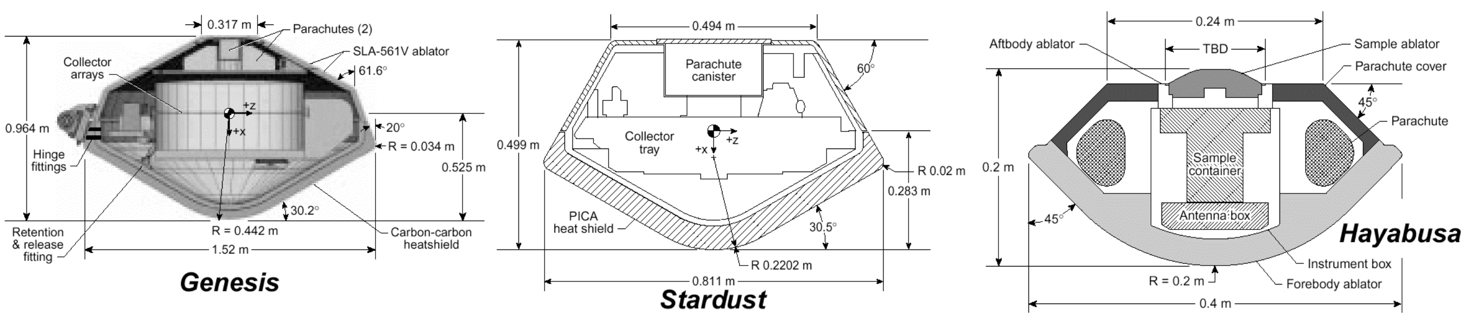
- Observation Data Reduction
  - Prasun Desai - trajectory reconstruction (LaRC)
  - Creon Levit - trajectory reconstruction (ARC)
  - Peter Jenniskens - airborne observation PI (SETI)
  - George Raiche - spectroscopy (ARC)
  - Mike Taylor - airborne observation (Utah St.)

- Flowfield Analysis
  - Iain Boyd - DSMC/CFD/Radiation (U-Mich)
  - Yen Liu - radiation lead (ARC)
  - Kerry Trumble - CFD lead (ARC)
  - Dinesh Prabhu - radiation (ARC)
  - David Saunders - tools (ARC)
  - Mike Wright - CFD (ARC)

SRC Overview

Stardust Post-flight Analysis

	Genesis	Stardust	Hayabusa
Date:	2004 Sept. 08	2006 Jan 16	2010, June?
Time (local):	9:54 a.m. MDT	3:00 a.m. MDT	3:00 a.m.
Mass, kg:	225	45.8	18
Diameter, m:	1.52	0.811	0.40
Entry speed (@135 km), km/s:	10.8	12.8	12.2
Kinetic energy (billion J)	13.6	3.8	1.3
Entry angle, deg.:	-8.0	-8.2	-13.8
Spin rate, rpm:	15	15	2
Forebody Peak heat rate, W/cm2.:	~700	~1000	~1500
Peak deceleration, Earth g's.:	28	34	45
Forebody TPS:	C-C facesheet Cfiberform	PICA	Carbon Phenolic
Afshell TPS:	SLA 561-V	SLA 561-V	?
Landing site:	UTTR	UTTR	Australia
Sample returned:	solar wind	comet dust	asteroid debris



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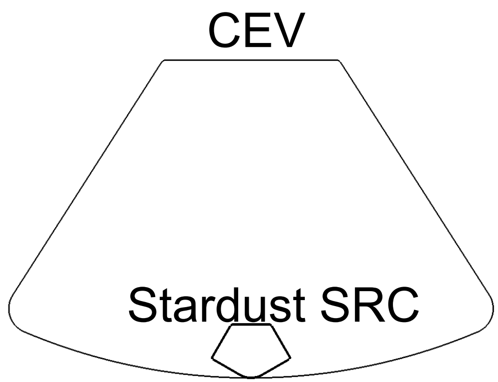
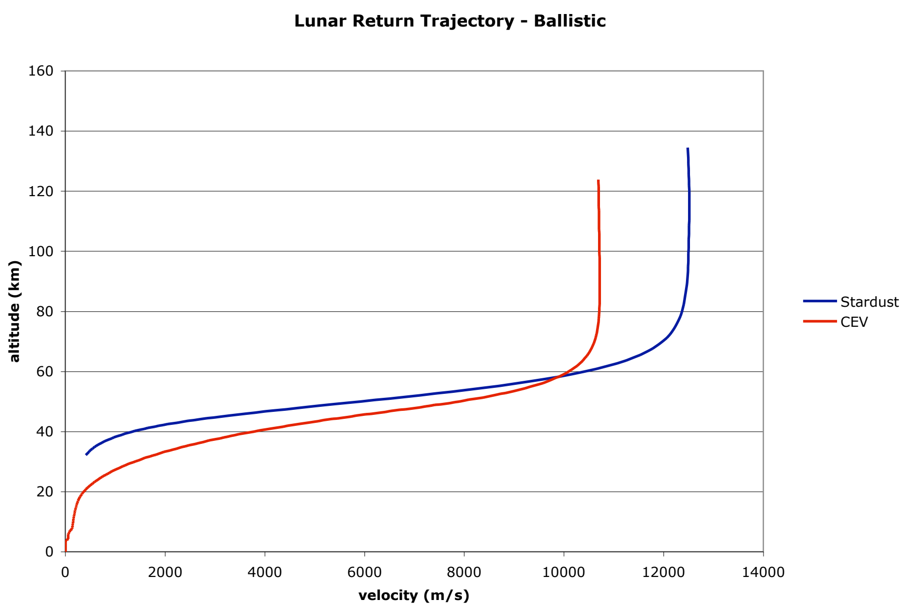
Stardust vs CEV





	Stardust	CEV
Peak Heat Flux (Total)	1000 W/cm^2	~ 900 W/cm^2
Peak Heat Flux (Radiative)	84 W/cm2	~ 400 W/cm^2
Peak Heat Load	28 kJ/cm^2	~ 70 kJ/cm^2
Location of Peak Heating	Stagnation Point at Geomteric Apex	Forward Facing Edge at Lifting Attitude

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Post-Flight Analysis Objectives

Stardust Post-flight Analysis

- Forebody Heatshield-

Forebody objectives encompass both aerothermal and material response

1. Determine unusual surface features indicating off-nominal aerodynamic performance, off-nominal TPS performance, or pre-entry damage.
2. Measure in-depth char and transition layer of TPS at select locations to determine spatially varying integrated heat load.
3. Measure in-depth properties of Phenolic Impregnated Carbon Ablator (PICA) TPS, e.g. density, chemical composition, and thermal properties, to compare to pre-flight models and arc-jet tested samples.
4. Measure residual bond strength to assess aging effects

- Aft-shell-

Aft-body objectives are mostly aerothermal

1. Determine unusual surface features indicating off-nominal aerodynamic performance, off-nominal TPS performance, or pre-entry damage.
2. Measure surface reflectivity as indicator of surface heating, flow pattern, or ablation product deposition.
3. Measure in-depth char and transition layer of TPS at select locations to determine spatially varying integrated heat load.

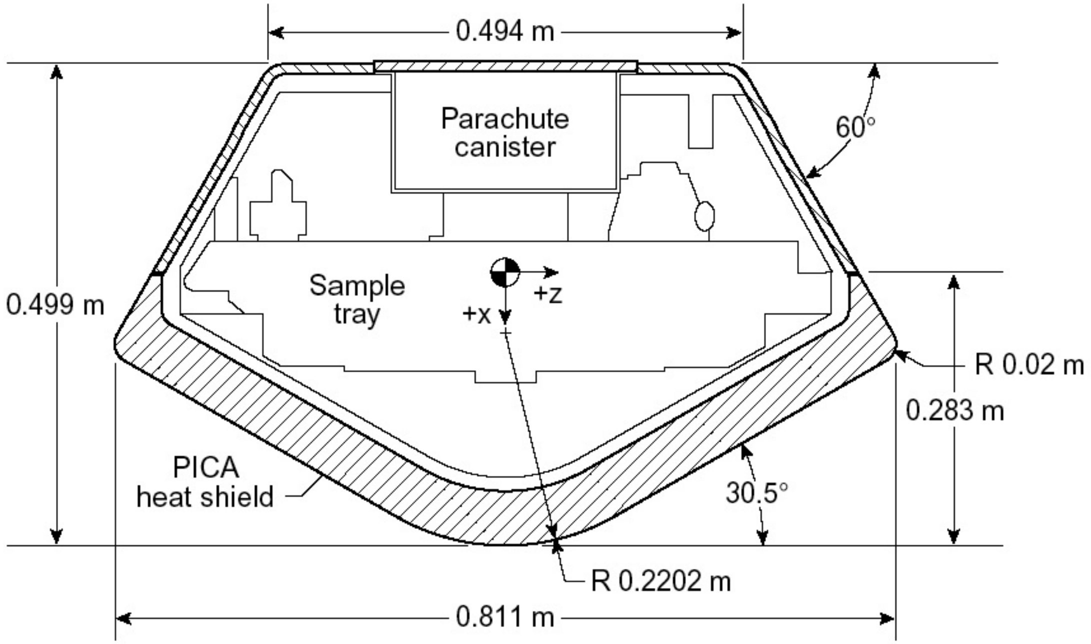
Are we about right in our analysis capability, are we able to determine if increasing complexity is actually an increase in fidelity, and what data would we want from a future CEV flight test?

Approach

- To meet objectives, leverage three sources of information:
  - airborne observation of SRC entry
    - video clip previously shown is from that observation
  - terminal descent radar
  - recovered hardware
- Prioritize those tasks of most relevance and immediacy to CEV
  - PICA forebody heatshield material is baseline TPS for CEV

Stardust Description

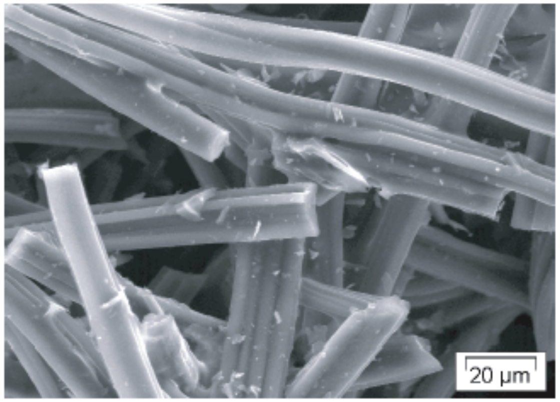
Stardust Post-flight Analysis



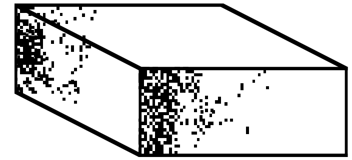
Forebody Heatshield: PICA @ 5.82 cm (2.29”) thick, constant
Forebody Substructure: Composite Facesheets, Aluminum Honeycomb
@ 1.27 cm (0.5”) thick, constant

Backshell TPS: SLA 561-V @ 1.02 cm (0.4”) thick
Backshell Substructure: Composite Facesheets, Aluminum Honeycomb
@ 1.27 cm (0.5”) thick
Backplate Substructure: Aluminum

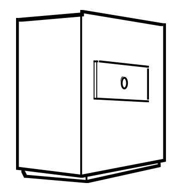
Phenolic Impregnated Carbon Ablator (PICA)



Fiberform before impregnation

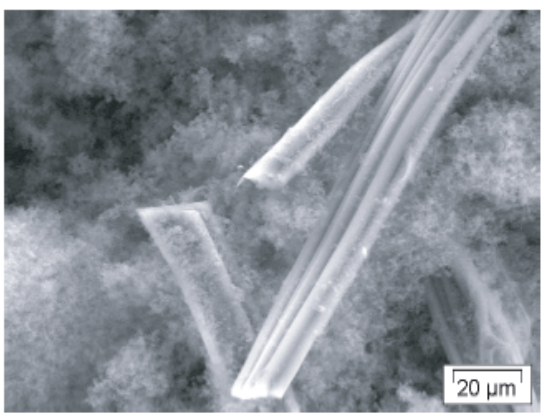


Carbon Fiberform Impregnated with Phenolic



Curing Cycle

PICA Billet



PICA with phenolic resin impregnated

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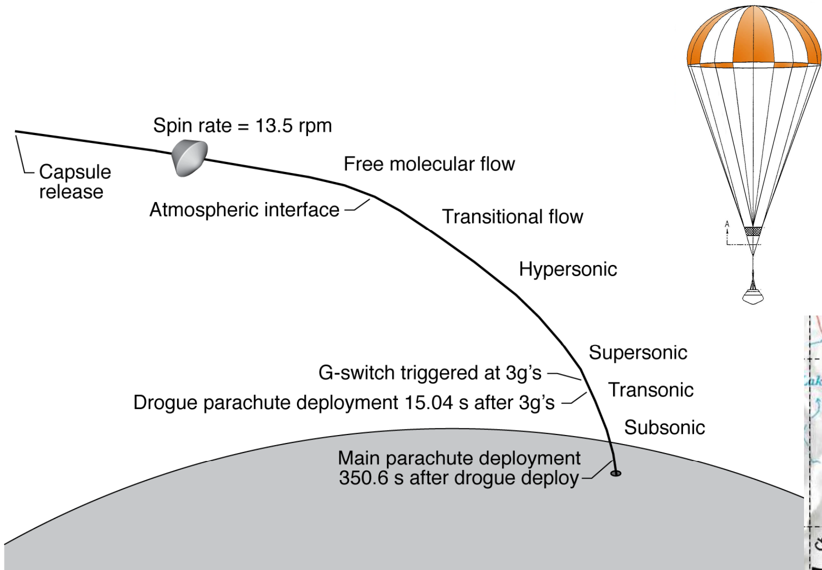
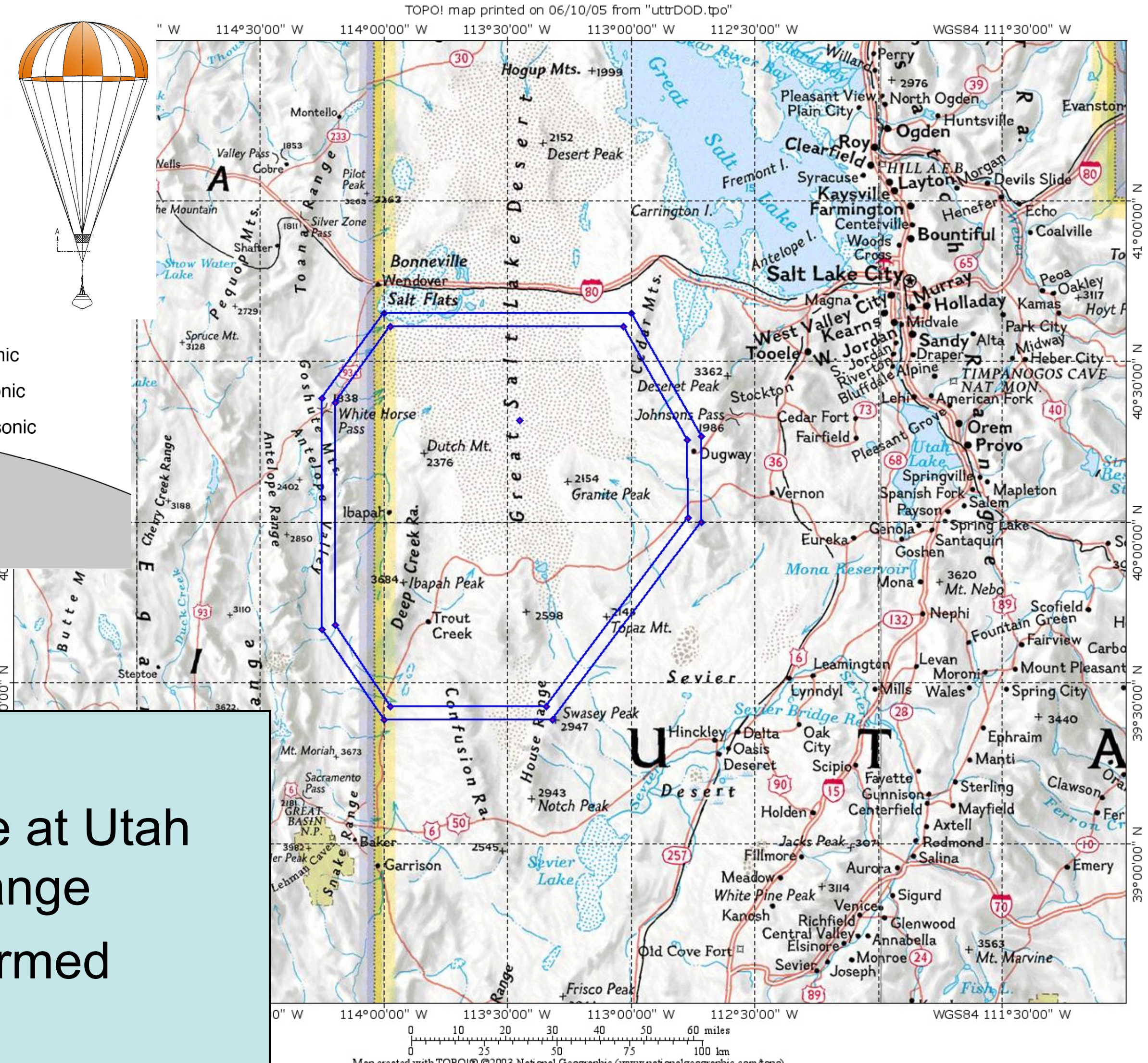
Entry, Descent and Landing

Stardust Post-flight Analysis

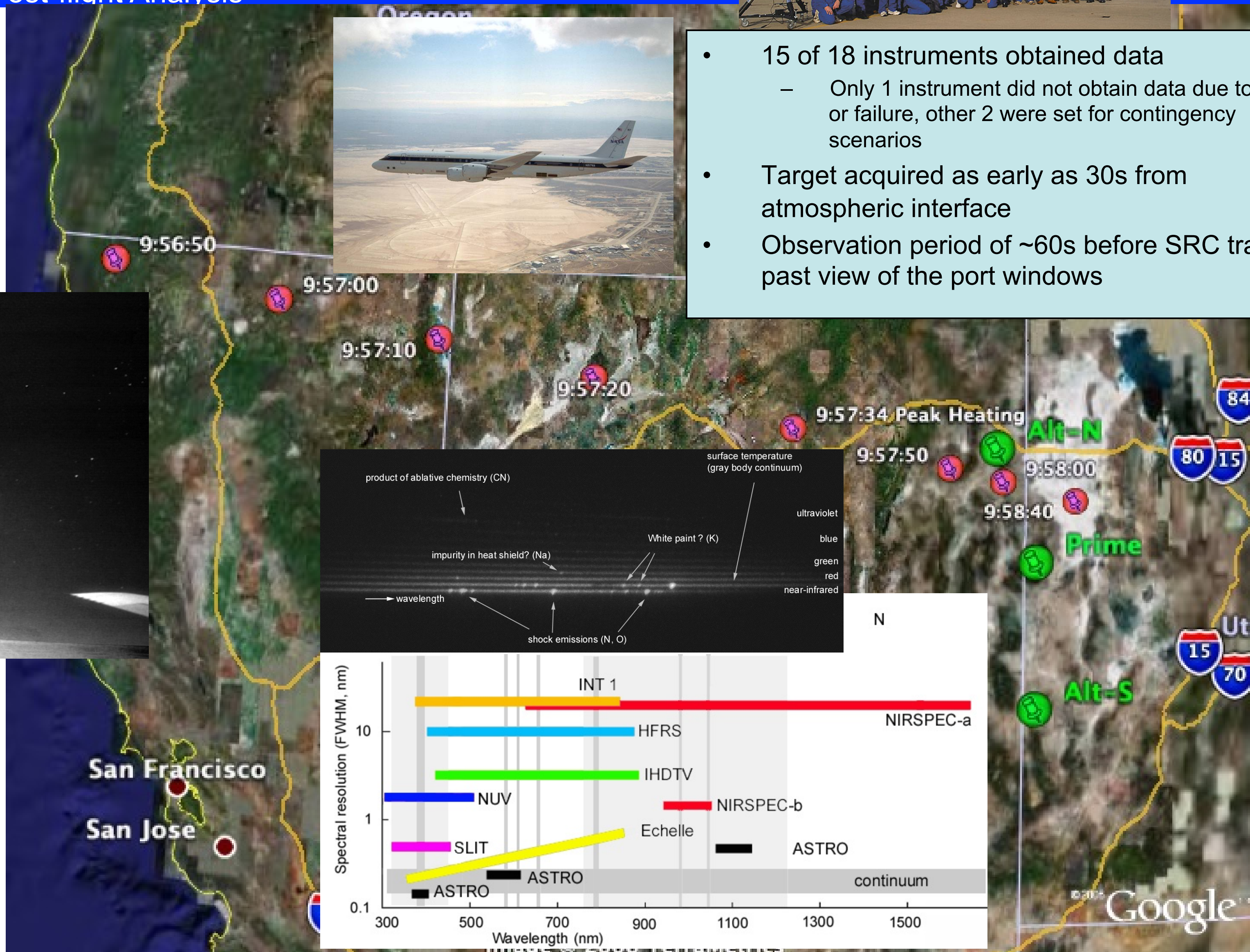




- ballistic entry
- land under parachute at Utah Test and Training Range
- EDL sequence performed nominally

Airborne Observation

Stardust Post-flight Analysis

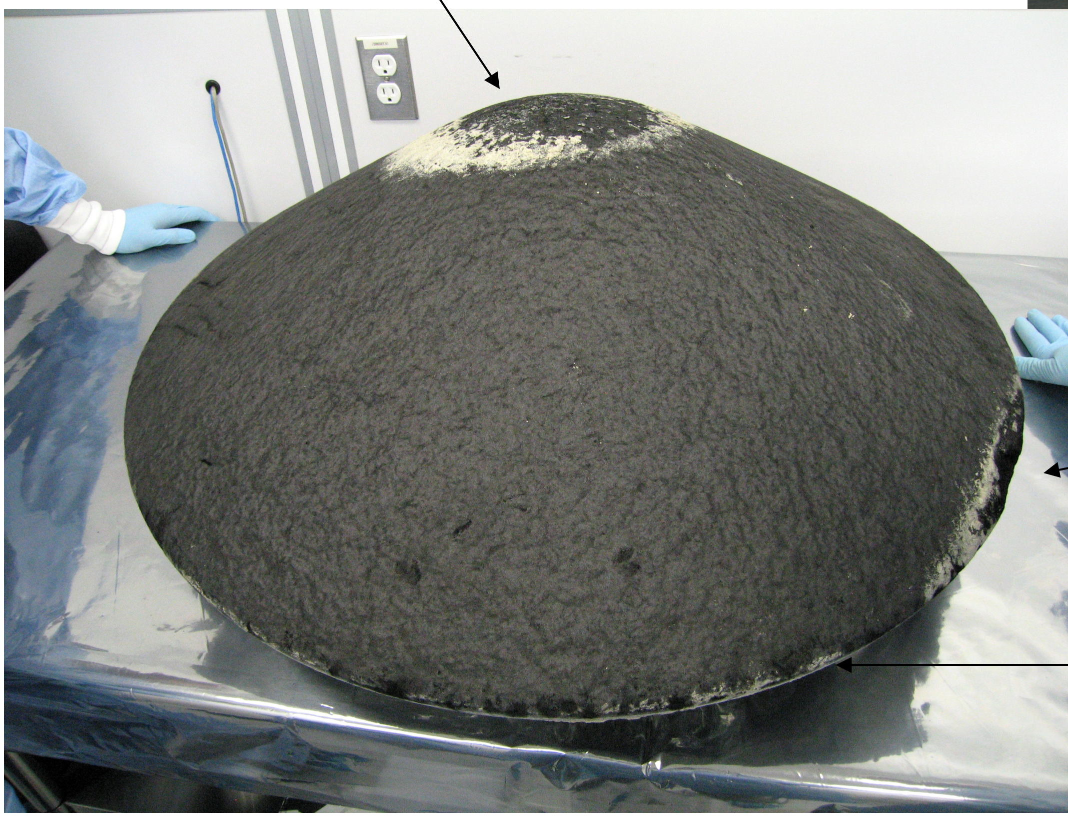


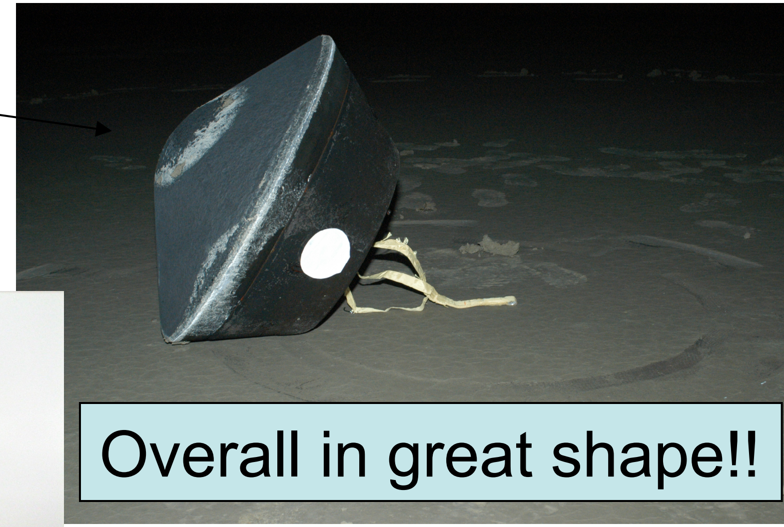
- 15 of 18 instruments obtained data
  - Only 1 instrument did not obtain data due to error or failure, other 2 were set for contingency scenarios
- Target acquired as early as 30s from atmospheric interface
- Observation period of ~60s before SRC travels past view of the port windows

Forebody Heatshield

Stardust Post-flight Analysis

First impact (while on the chute) at nose region, off-center (soil ring visible)





Overall in great shape!!

Broken piece at maximum diameter

Rolled on edge (soil visible)

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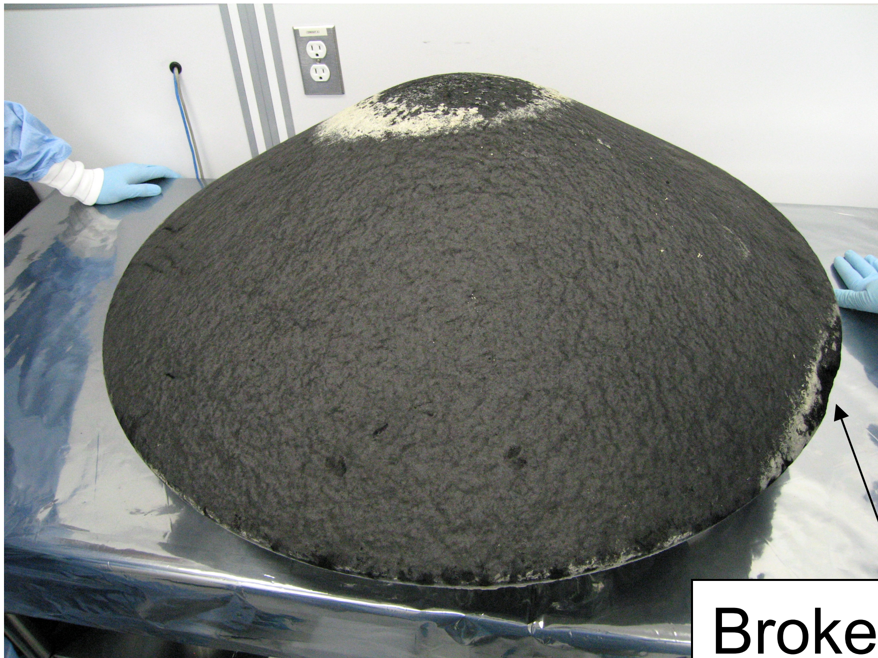
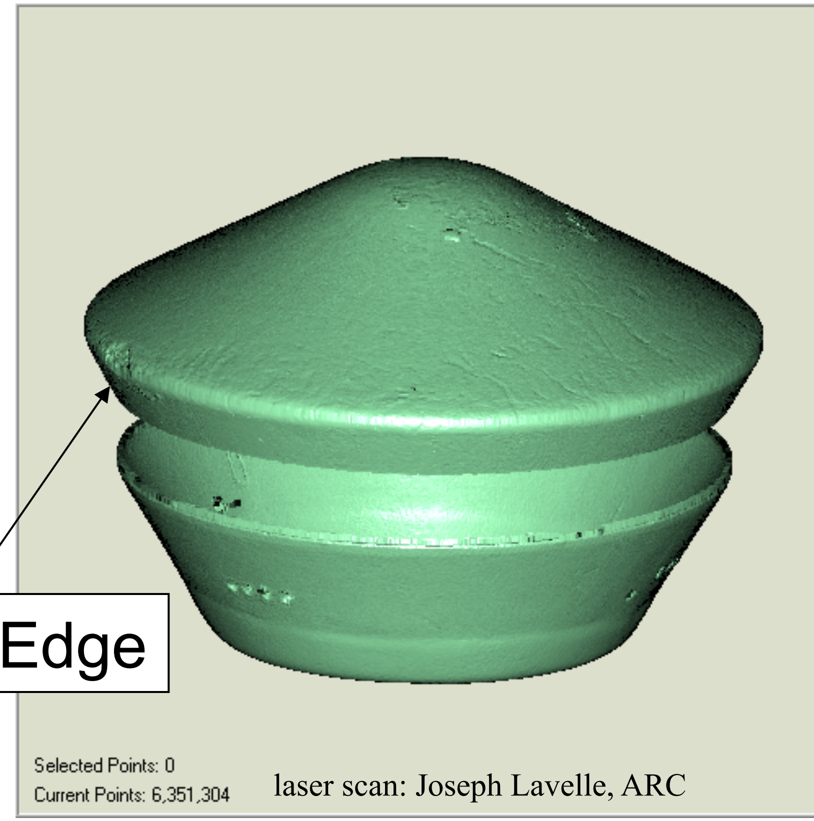
Geometry Determination

Stardust Post-flight Analysis





- Forebody and aft-shell laser scanned to determine post-flight shape
  - at least 1 mm surface resolution

Stardust Forebody Cores

Through conversations between the NASA post-flight analysis team and Lockheed Martin Space Systems, and consistent with proposals approved by Curation and Discovery program, agreement was reached for the following approach:

Three 2” Diameter core regions identified:

1) **Stagnation Core** - centered 2.5 inches from sphere-cone apex on the 40 degree radial line. That area seems to be opposite the landing damage and still has dirt on it meaning no PICA came off. It is on the spherical nosecap but not on the apex.

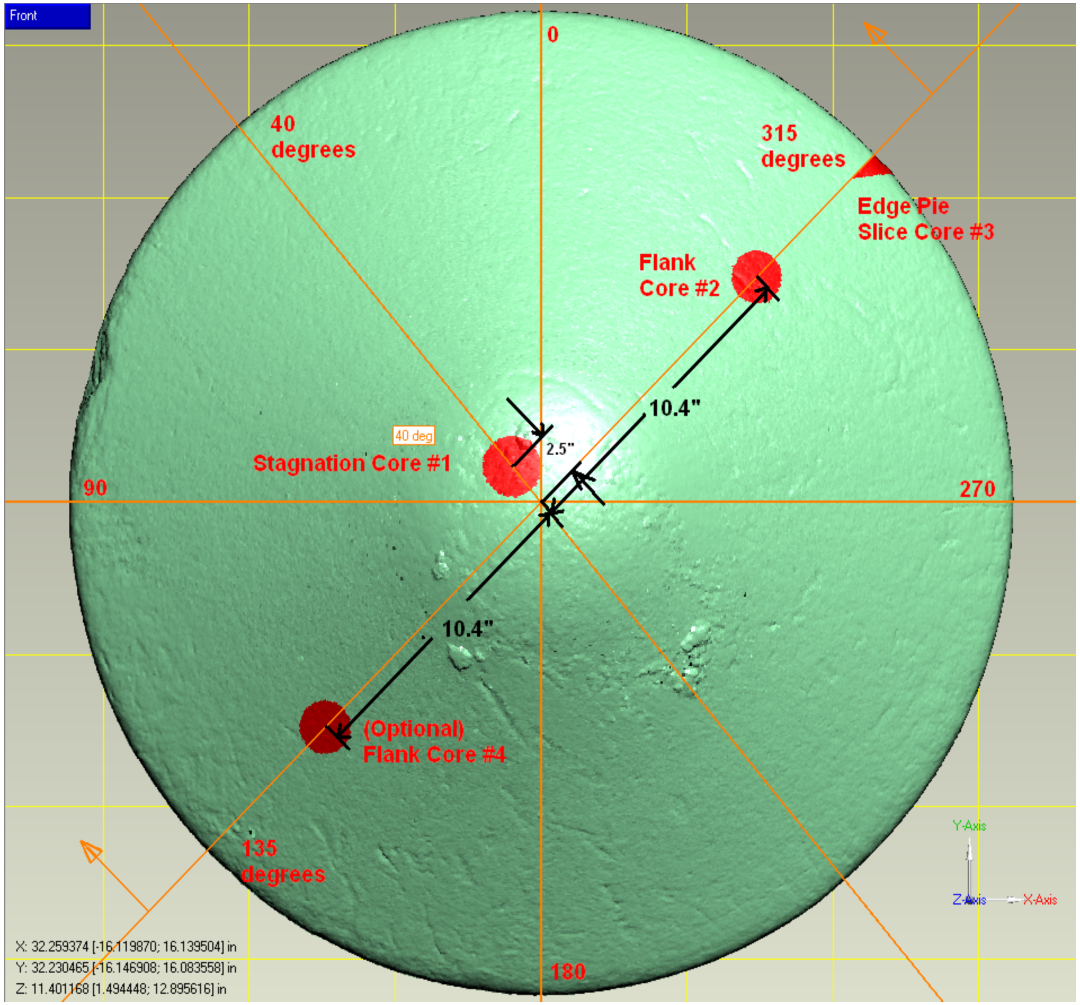
2) **Mid-flank Flank Core** - at the 315 degrees, appears clean and away from landing damage.

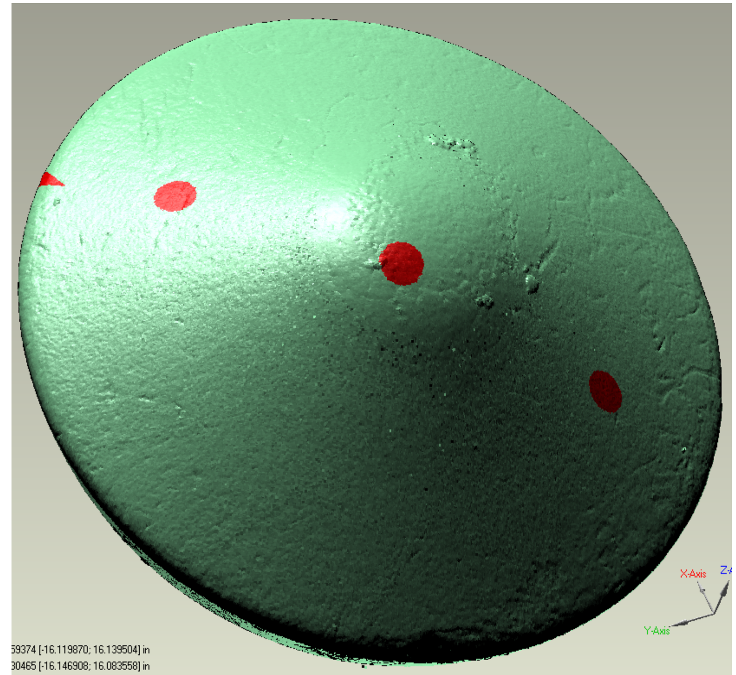
3) **OPTIONAL Mid-flank Core** - at 135 degrees exactly opposite other mid-flank core

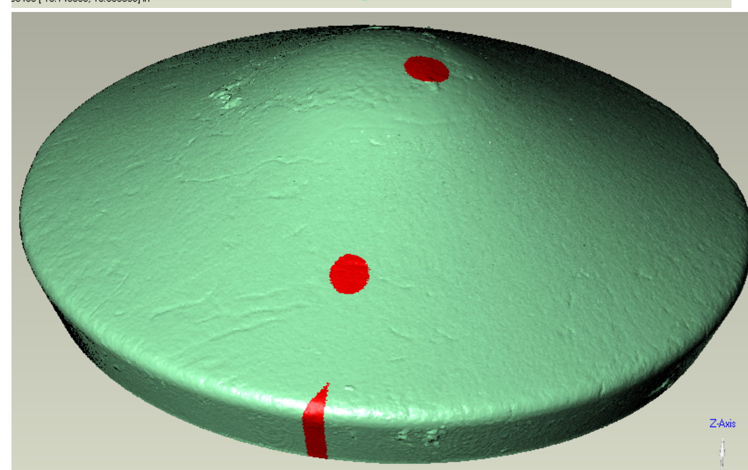
Pie Slice - taken from the maximimum diameter at 315 degrees

Forebody Core Map (Top View)

Stardust Post-flight Analysis







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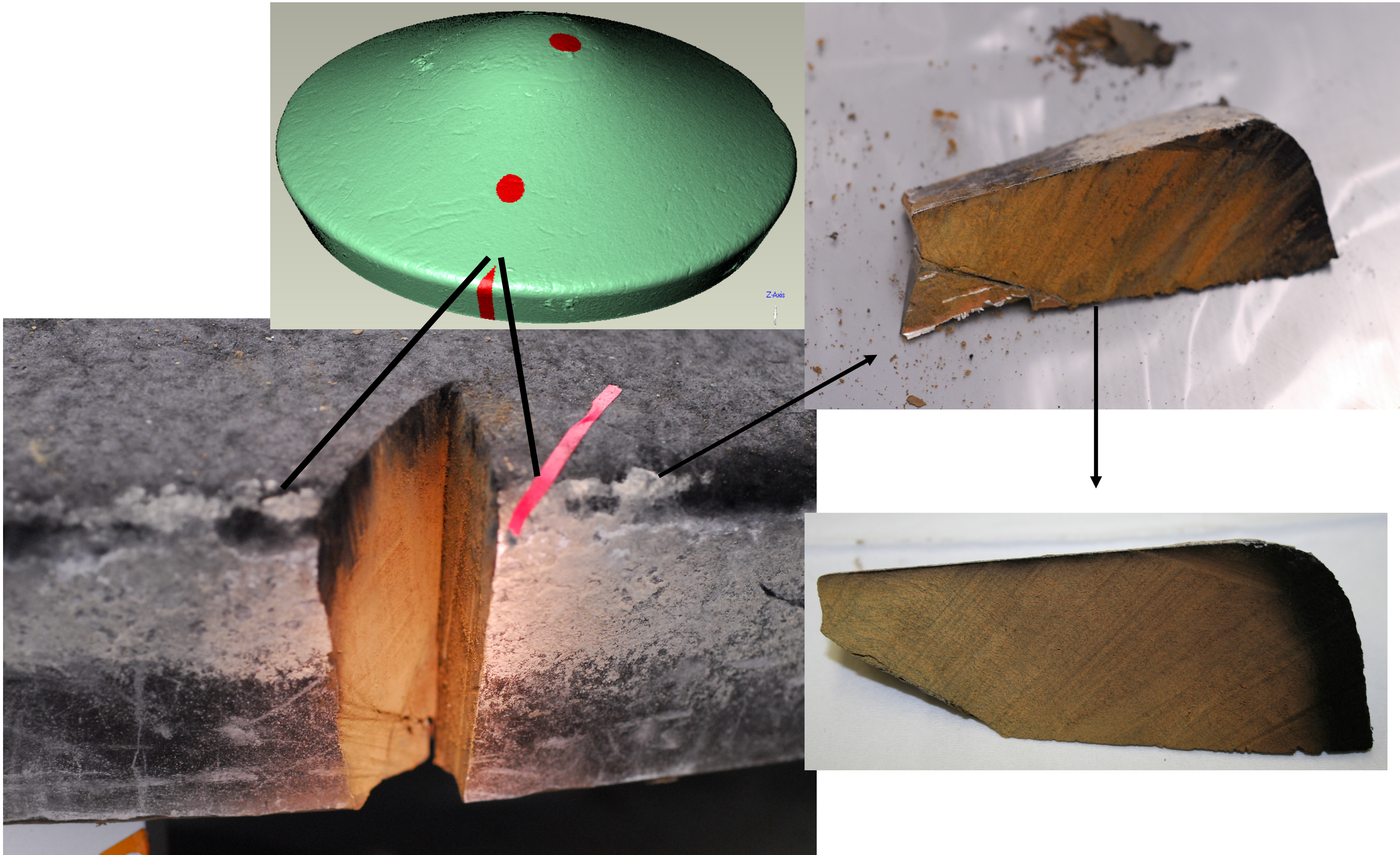
Edge Slice

Stardust Post-flight Analysis



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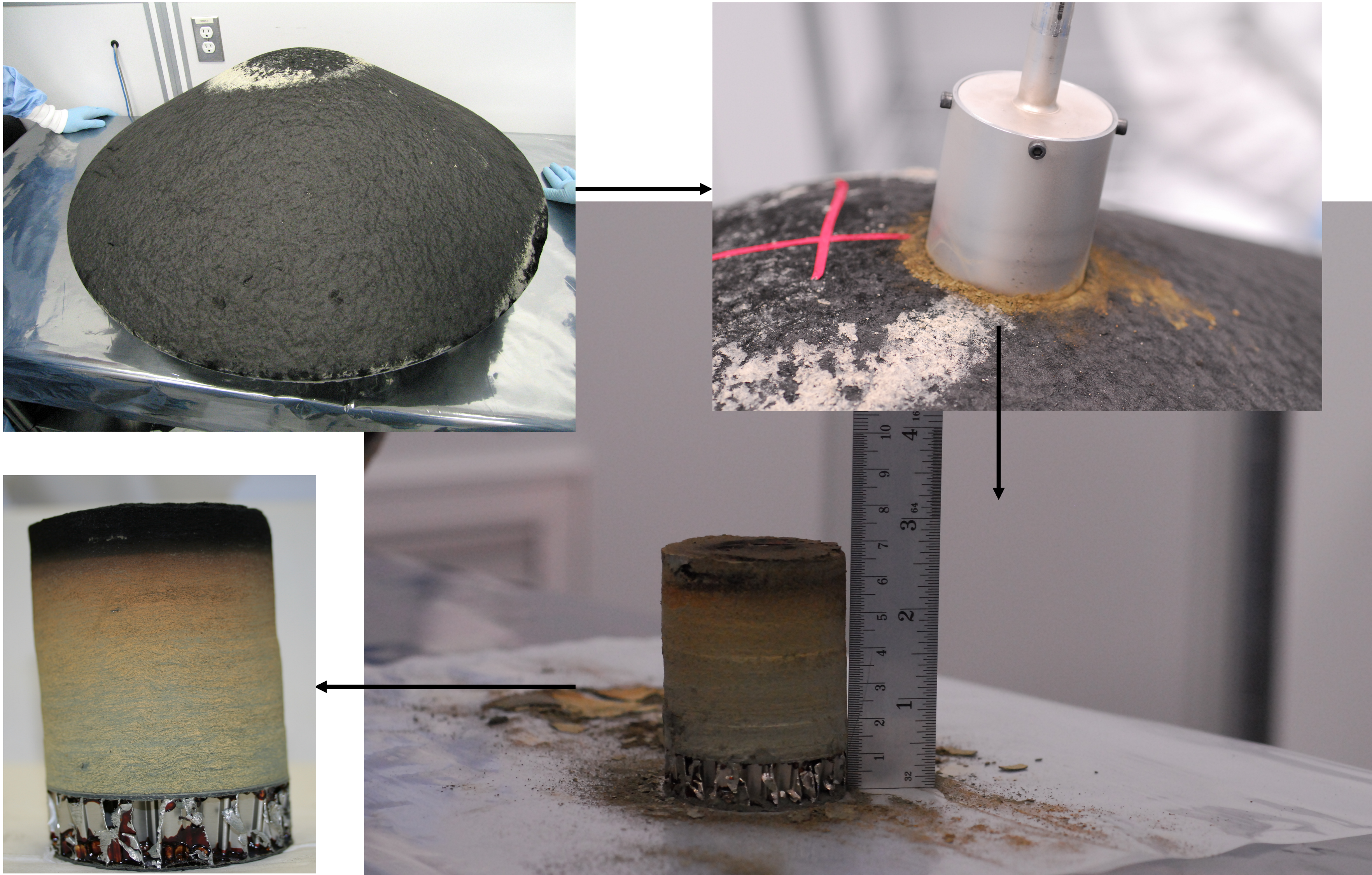
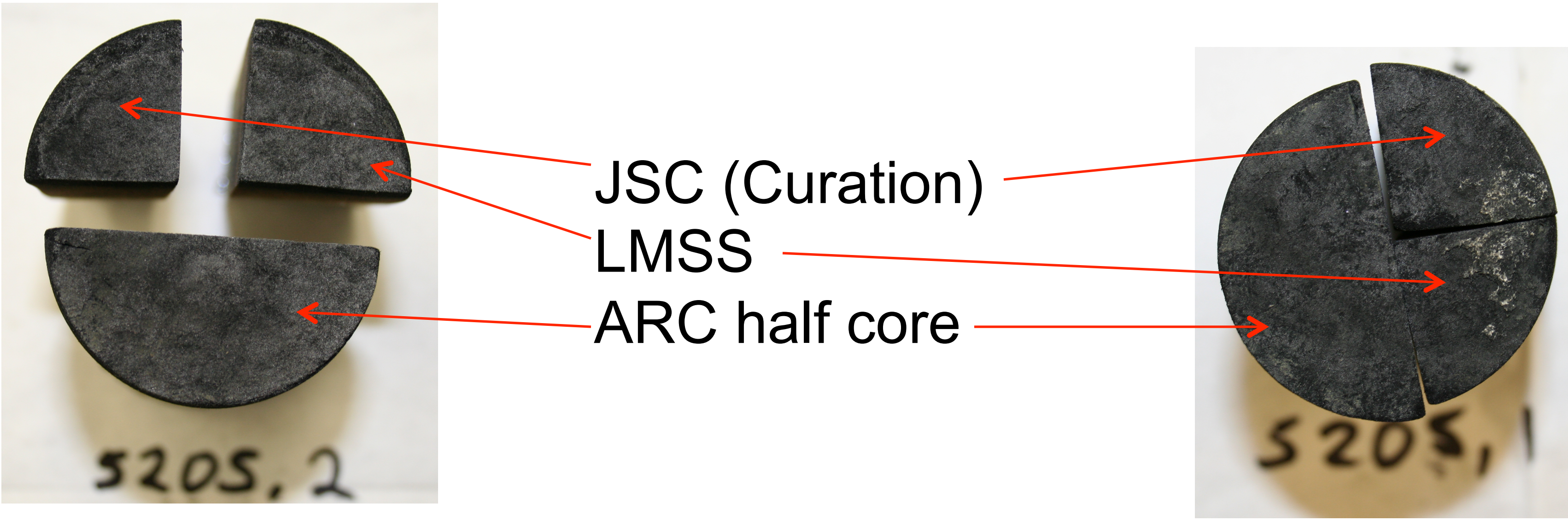
Stardust Heatshield

Stardust Post-flight Analysis



Core Subdivision



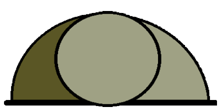
Flank core
ID # 5205,2

Stagnation core
ID # 5205,1

- Cores partitioned
  - Half retained at Ames Research Center (ARC) for analysis
  - Quarter to Johnson Space Center (JSC) for curation
  - Quarter to JSC to forward to Lockheed Martin Space Systems (LMSS)

Core Sectioning

The core is sectioned into slices (slice thickness < 1mm)



Each slice is further sectioned into a 1" cylinder/disc and 2 remnants (Remnants to be used primarily for destructive analysis)

Density of each cylinder obtained knowing the mass and dimensions of the cylinder. This approach is non-destructive to the slice which can then be used for further analysis

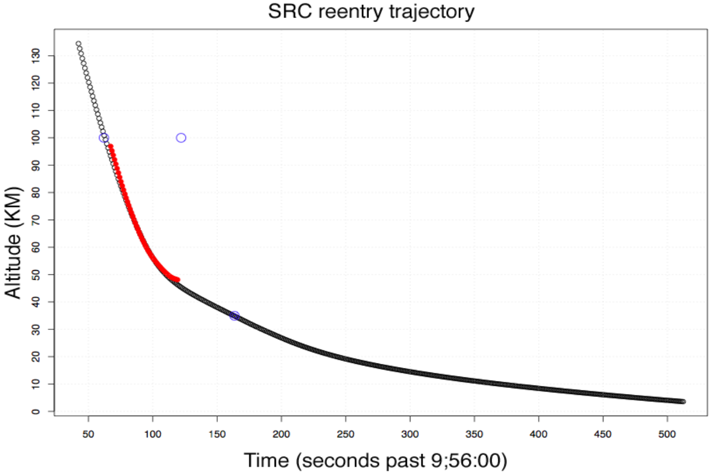
Analysis

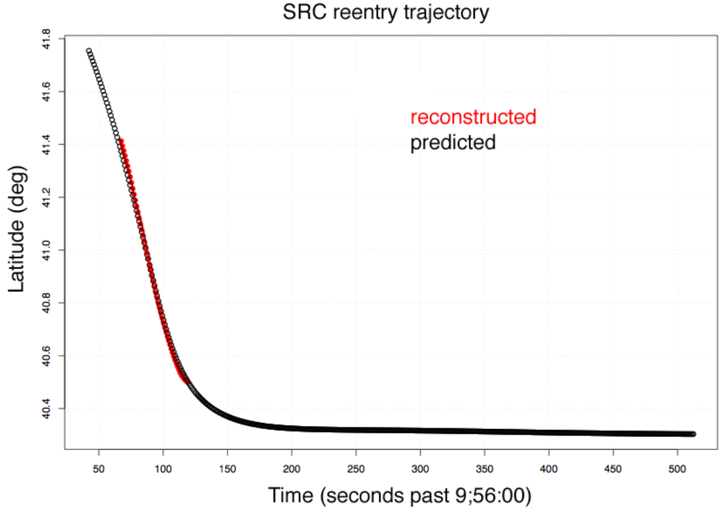
Trajectory Determination

Stardust Post-flight Analysis

Photo: Bruce Fischer, Wendover Airfield, UT.

- Data Sources
  - UTTR radar tracking
  - Airborne observation
  - Ground Photos





Based on available data, the pre-entry predicted trajectory is used as the Best Estimated Trajectory.

Predicted Trajectory: Prasun Desai, LaRC
Reconstructed Traj: Creon Levit, ARC

Aerothermal and TPS Response Tools

- Flowfield
  - DPLR v3.05
  - 11 species air, thermal and chemical non-equilibrium
  - Radiative equilibrium surface boundary condition
  - Fully catalytic
  - Axisymmetric - base flow included
- Material Response
  - FIAT v2.1 : in-depth conduction, ablative response
  - PICA Model: “PAT Model”, v2.00
  - 1D Material Stack from surface through substructure
  - Input heat transfer coefficient from DPLR, surface energy balance
- Radiative Production and Transport
  - NEQAIR
  - 1D line-of-sight, tangent slab
  - post-process DPLR flowfield result (non-coupled)

DPLR Solutions

Stardust Post-flight Analysis

STARDUST
Nominal Entry Trajectory Data: s06015f_traj_profile_atm.txt

D = **0.8128**

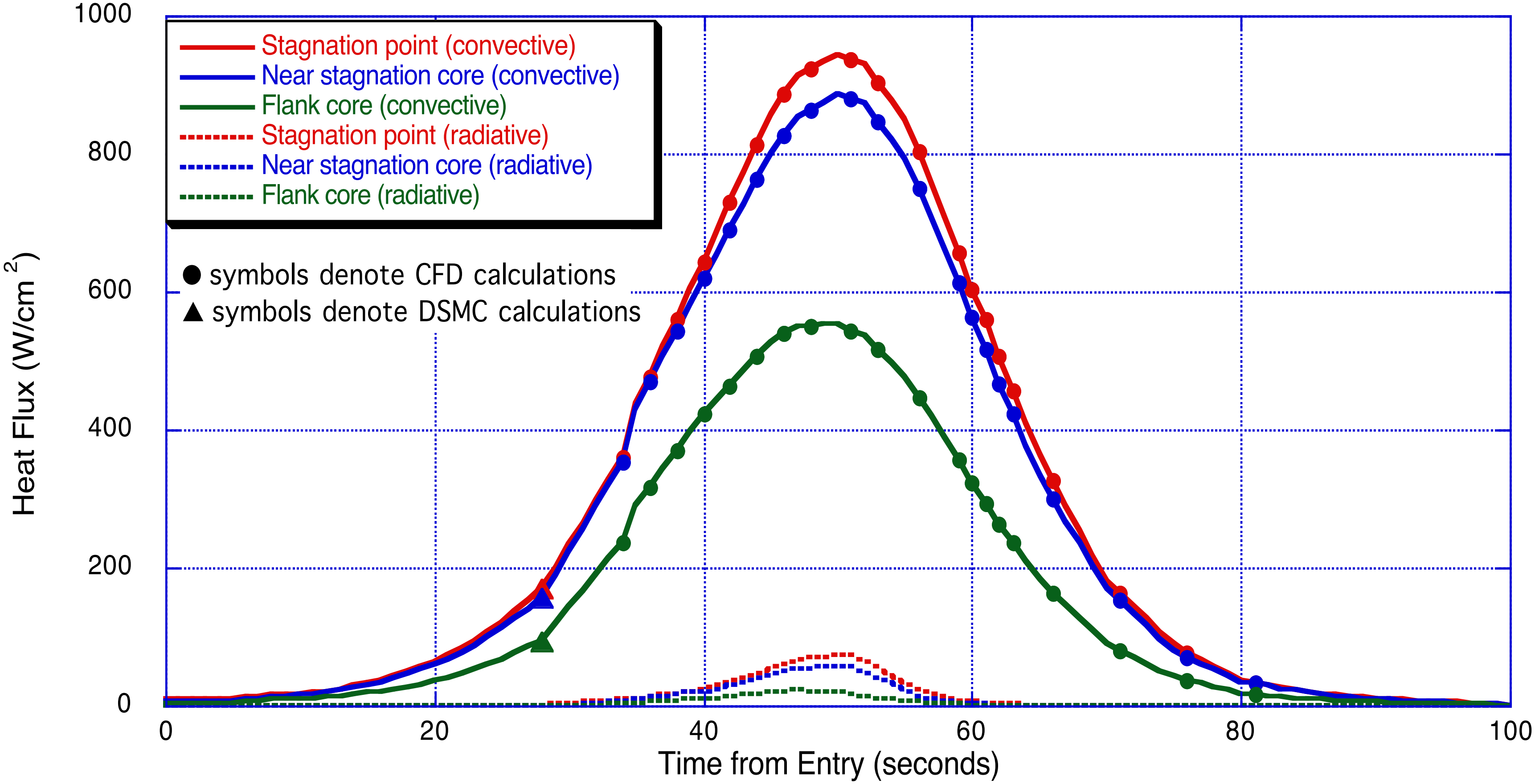
Time of Entry: 15-JAN-2006, 9:56:42.3026 UTC, 0.000 s (from EI)
Time of Peak Heating: 15-JAN-2006, 9:57:33.3026 UTC, 51.000 s (from EI)
Time of Drogue Deployment: 15-JAN-2006, 9:58:55.3026 UTC, 133.000 s(from EI)

			Freestream								
UTC	**Time from EI** *(s)*	**Altitude** *km*	**Velocity** *m/s*	**Density** *(kg/m3)*	**Temperature** *(K)*	**Pressure** *(Pa)*	**M**	**nu** *(m2/s)*	**mfp** *(m)*	**Re_D**	**Kn_D**
57:16.3	34.000	81.025	12385.120	1.26900E-05	217.63	0.79216	4.18E+01	*1.20E+00*	*6.02E-03*	8.36E+03	7.41E-03
57:18.3	36.000	78.458	12336.861	1.87100E-05	218.09	1.17052	4.16E+01	8.18E-01	4.09E-03	1.23E+04	5.03E-03
57:20.3	38.000	75.961	12269.128	2.72400E-05	218.69	1.71097	4.13E+01	5.63E-01	2.81E-03	1.77E+04	3.46E-03
57:22.3	40.000	73.540	12181.085	3.92200E-05	219.96	2.47836	4.09E+01	3.93E-01	1.95E-03	2.52E+04	2.41E-03
57:23.3	41.000	72.357	12126.577	4.67600E-05	220.80	2.96542	4.06E+01	3.30E-01	1.64E-03	2.98E+04	2.02E-03
57:24.3	42.000	71.195	12062.734	5.55200E-05	221.62	3.53337	4.03E+01	2.79E-01	1.38E-03	3.51E+04	1.70E-03
57:26.3	44.000	68.934	11902.133	7.72200E-05	224.14	4.96797	3.96E+01	2.02E-01	9.98E-04	4.78E+04	1.23E-03
57:28.3	46.000	66.761	11689.113	1.05310E-04	227.56	6.8736	3.86E+01	1.50E-01	7.35E-04	6.33E+04	9.04E-04
57:30.3	48.000	64.685	11414.006	1.40990E-04	230.79	9.32773	3.74E+01	1.13E-01	5.51E-04	8.18E+04	6.78E-04
57:33.0	51.000	61.761	10871.381	2.11000E-04	234.95	14.21781	3.53E+01	7.68E-02	3.70E-04	1.15E+05	4.55E-04
57:35.3	53.000	59.954	10417.960	2.69640E-04	237.68	18.38463	3.36E+01	6.07E-02	2.90E-04	1.40E+05	3.57E-04
57:36.3	54.000	59.092	10166.280	3.02480E-04	239.48	20.78098	3.27E+01	5.44E-02	2.59E-04	1.52E+05	3.19E-04
57:37.3	55.000	58.258	9898.939	3.37670E-04	241.32	23.37776	3.17E+01	4.90E-02	2.33E-04	1.64E+05	2.87E-04
57:38.3	56.000	57.455	9617.356	3.75060E-04	243.10	26.15734	3.07E+01	4.44E-02	2.10E-04	1.76E+05	2.58E-04
57:39.3	57.000	56.684	9323.620	4.14510E-04	244.80	29.11116	2.97E+01	4.04E-02	1.90E-04	1.88E+05	2.34E-04
57:40.3	58.000	55.942	9019.973	4.56080E-04	246.44	32.24575	2.86E+01	3.69E-02	1.73E-04	1.99E+05	2.13E-04
57:41.3	59.000	55.225	8708.655	4.99830E-04	248.00	35.56308	2.75E+01	3.38E-02	1.58E-04	2.09E+05	1.95E-04
57:42.3	60.000	54.538	8391.773	5.45700E-04	249.36	39.04419	2.65E+01	3.11E-02	1.45E-04	2.19E+05	1.79E-04
57:43.3	61.000	53.881	8071.742	5.93350E-04	250.56	42.66601	2.54E+01	2.87E-02	1.34E-04	2.29E+05	1.65E-04
57:44.3	62.000	53.253	7751.200	6.42610E-04	251.70	46.42858	2.43E+01	2.66E-02	1.24E-04	2.37E+05	1.52E-04
57:45.3	63.000	52.647	7432.344	6.93620E-04	252.80	50.34373	2.33E+01	2.47E-02	1.15E-04	2.44E+05	1.41E-04
57:48.3	66.000	50.980	6504.453	8.54350E-04	255.84	62.78974	2.02E+01	2.03E-02	9.35E-05	2.61E+05	1.15E-04
57:53.3	71.000	48.620	5128.163	1.15819E-03	257.35	85.61529	1.59E+01	1.50E-02	6.91E-05	2.78E+05	8.50E-05
57:58.3	76.000	46.663	4007.613	1.50208E-03	256.98	110.81337	1.24E+01	1.16E-02	5.32E-05	2.82E+05	6.55E-05
58:03.3	81.000	44.988	3132.724	1.87608E-03	256.55	138.10315	9.74E+00	9.24E-03	4.26E-05	2.75E+05	5.24E-05
58:22.3	100.000	39.892	1335.989	3.89546E-03	244.89	273.35653	4.25E+00	4.30E-03	2.03E-05	2.53E+05	2.49E-05

Red shade - peak heating
Yellow shade - Echelle observation period, high spectral resolution
Yellow and Blue Shade - NIRSPEC observation period, broadband

Results: Heat Flux

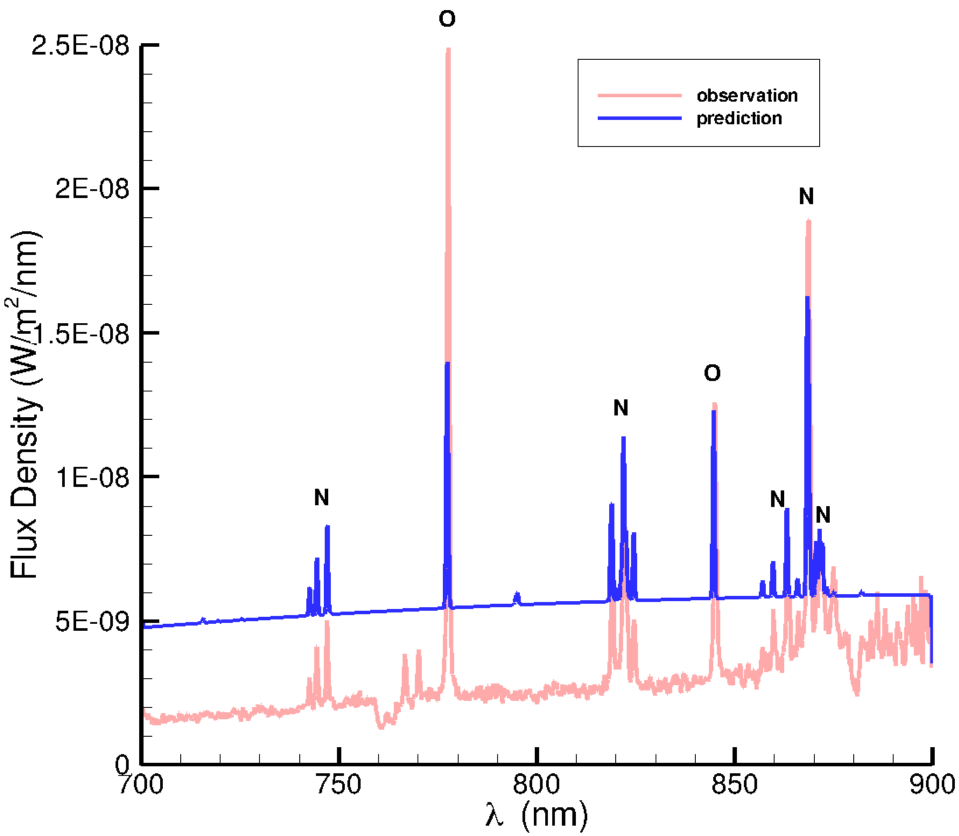
Stardust Post-flight Analysis



Stagnation Heat Load = 26.8 kJ/cm^2
Near Stagnation Core Heat Load = 25.3 kJ/cm^2
Flank Core Heat Load = 15.7 kJ/cm^2

Air Emission Analysis

Stardust Post-flight Analysis

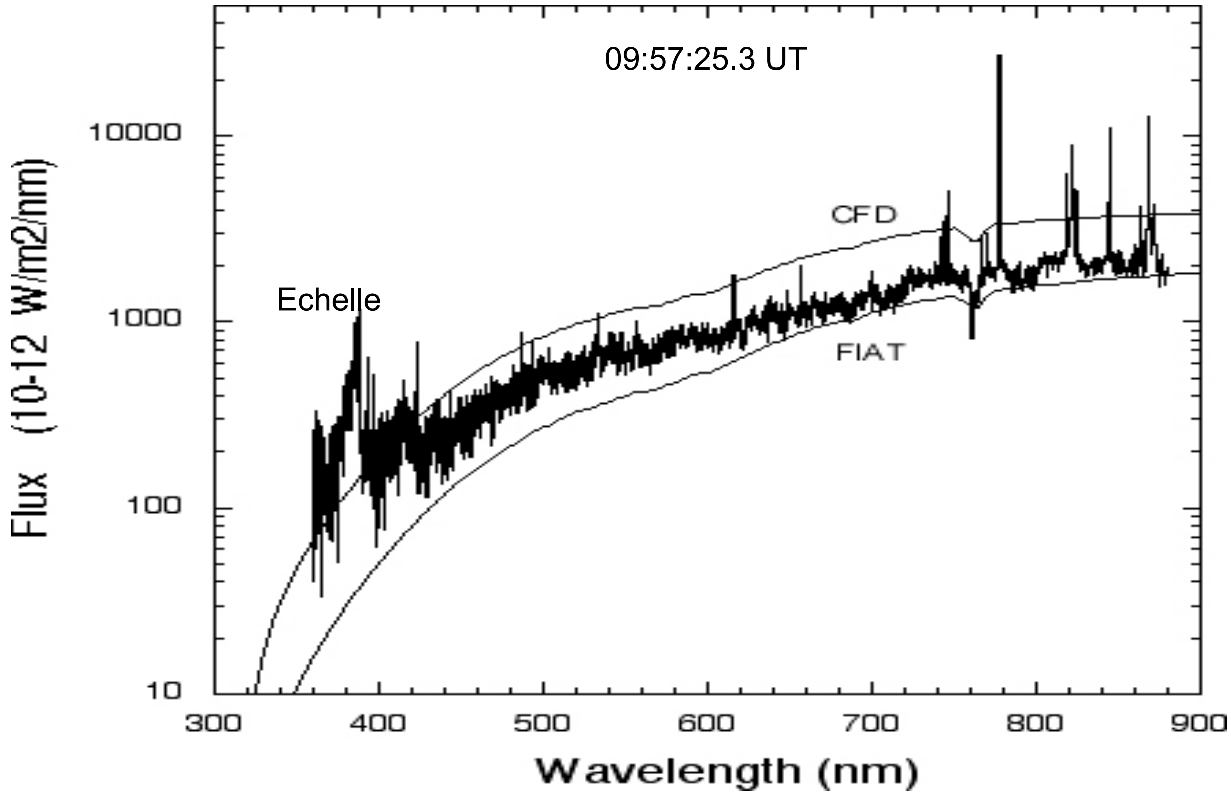


- simulated spectrum integrated over multiple lines-of-site parallel to observation vector
- simulated spectrum based on radiative equilibrium surface temperature
  - over-estimated surface temperature and hence higher broadband emission
- reasonable reproduction of Nitrogen and Oxygen lines
  - some anomalies being investigated

Simulated spectrum compared to Echelle observation data at 42 s from entry, altitude 71.2 km

Area-Average Surface Temperature

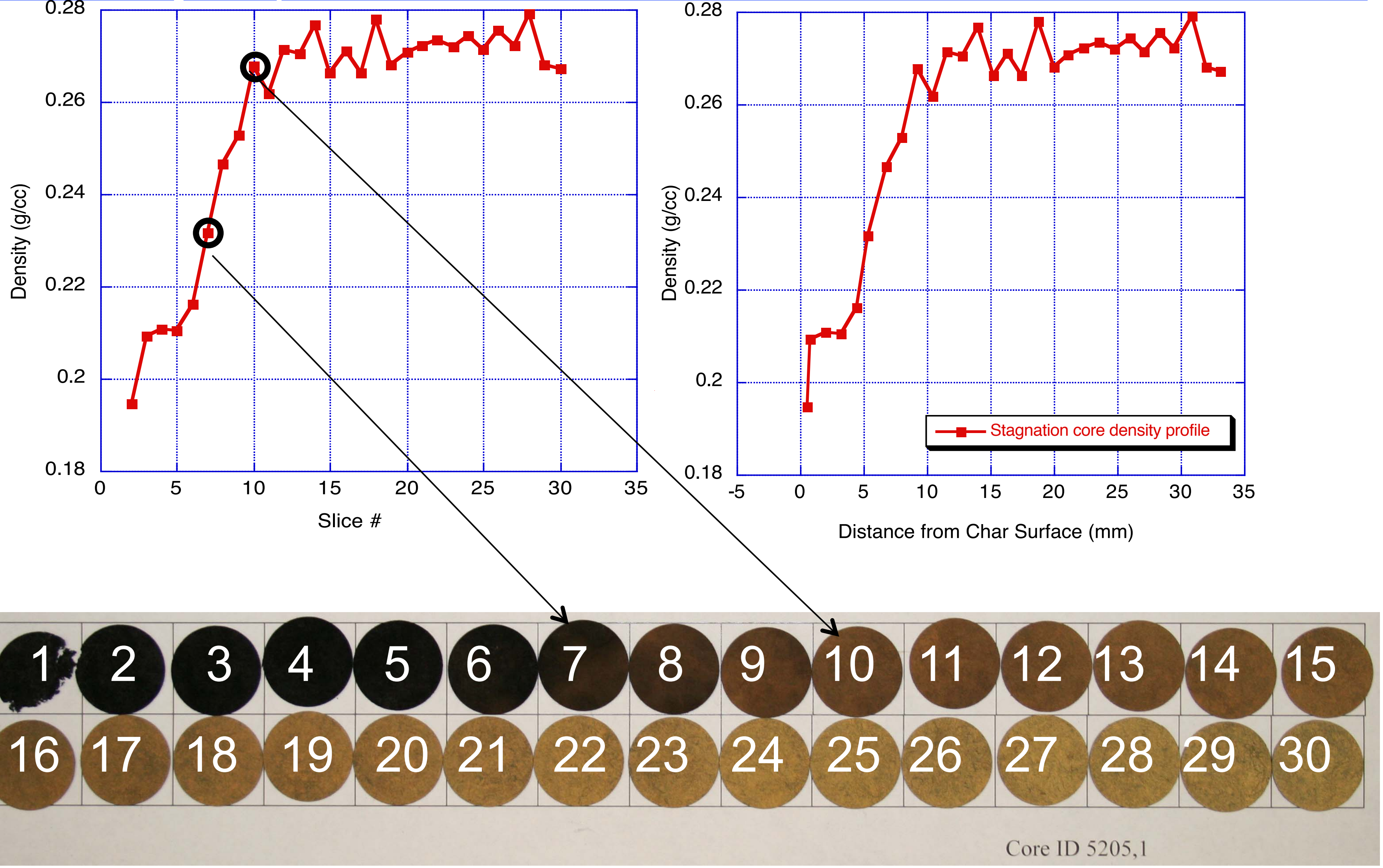
- broadband signal from observation dominated by hot forebody heatshield
- acquired broadband signal modified to account for emissivity, view angle, and atmospheric absorption
- simulated broadband signal developed by processing surface temperature distribution and view angle
- Two simulated curves:
  - 'CFD' is radiative equilibrium surface temperature, which should overpredict surface temperature because it does not account for in-depth conduction of the heat
  - 'FIAT' is the surface temperature predicted by accounting for the material response including conduction and ablation



	CFD	Echelle	FIAT
Area Average Surface Temperature (K)	3036	2685	2635

Density Profile of Near Stagnation Core

Stardust Post-flight Analysis



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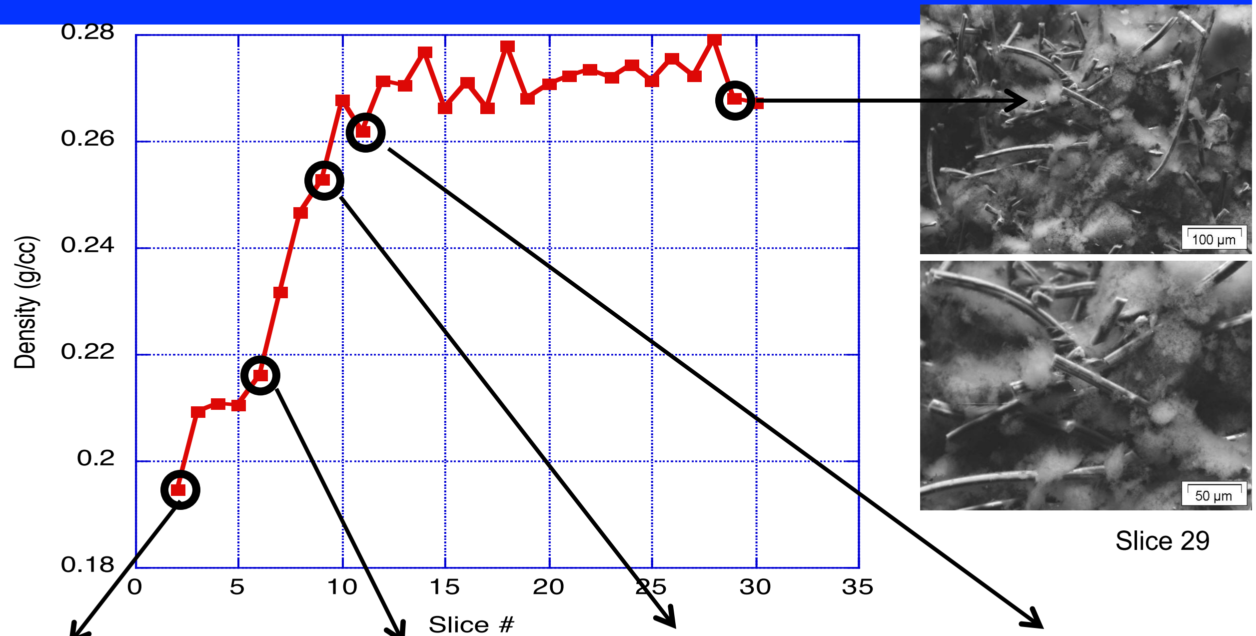
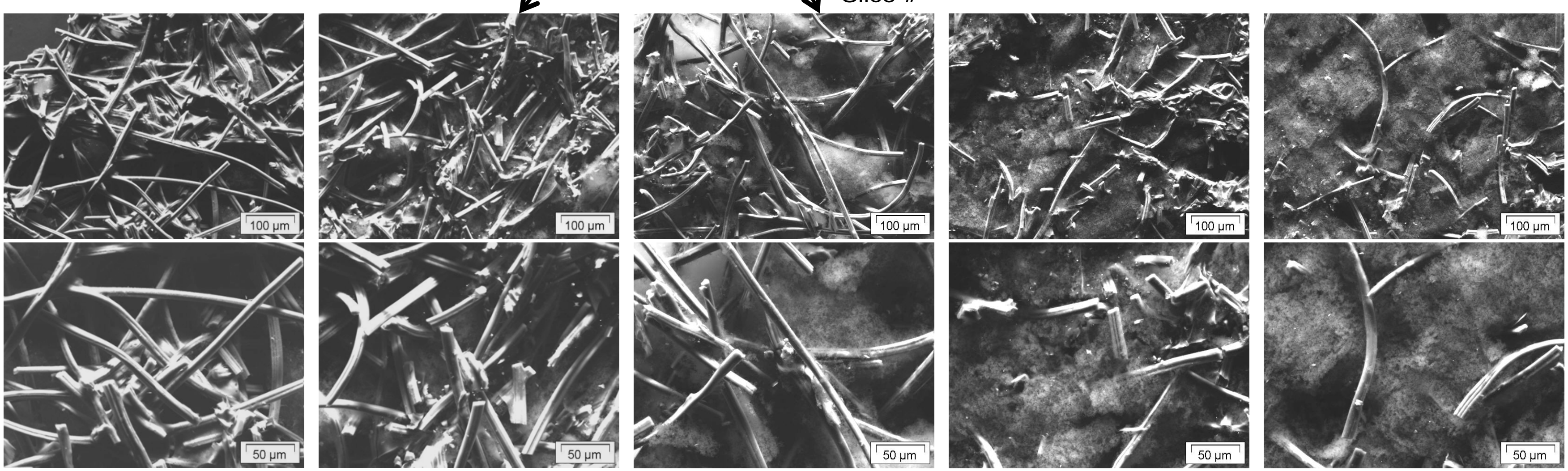
Microstructure of Near Stagnation Core

Stardust Post-flight Analysis

- Phenolic high surface area phase is absent in slices 1 and 2
- Density of starting fiberform is ~0.16 - 0.18g/cc
  - good agreement between this density and density of slices 1 - 2
- No apparent evidence of C fiber oxidation



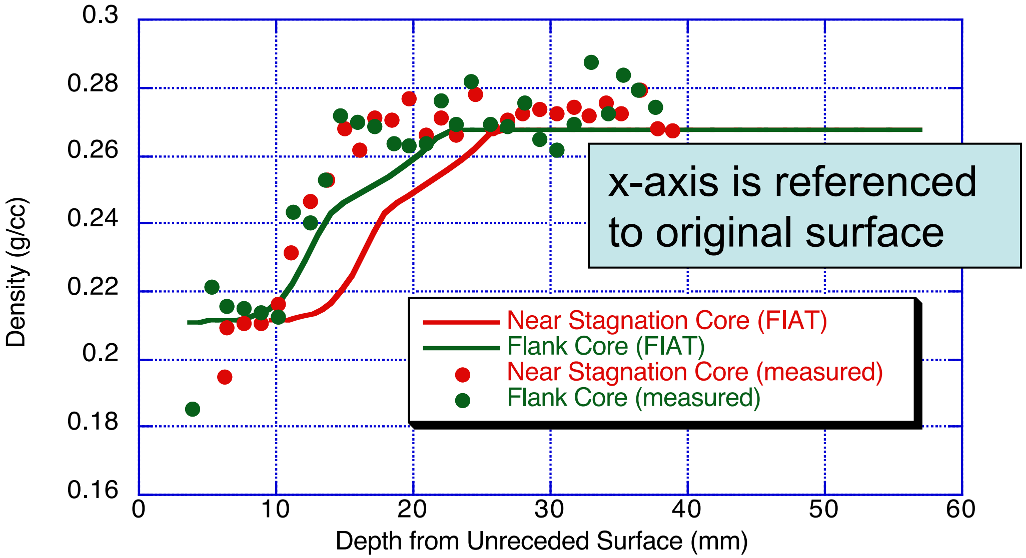
Slice 29

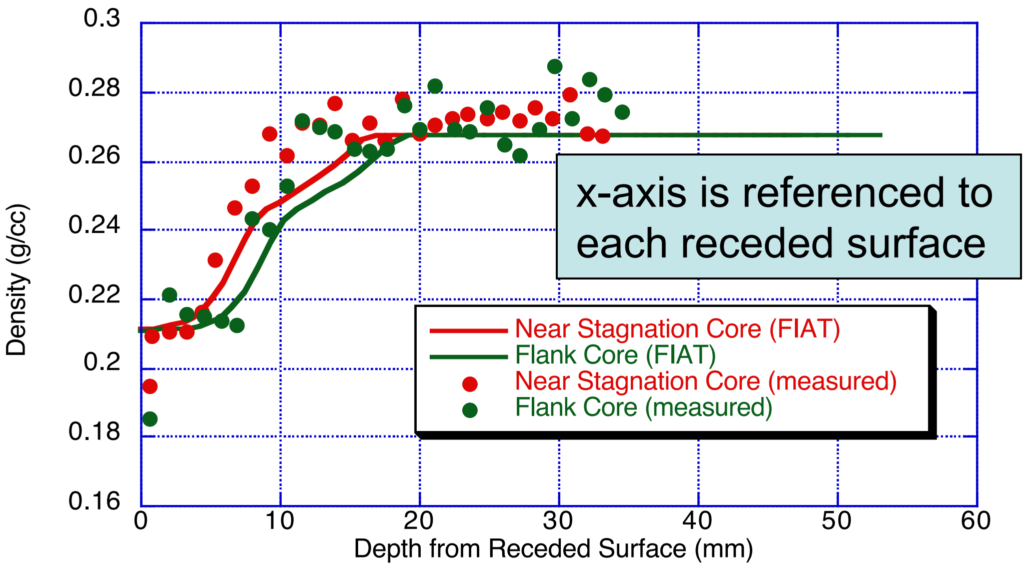


Slice 1 Slice 2 Slice 6 Slice 9 Slice 11

Results: Density and Recession

Stardust Post-flight Analysis



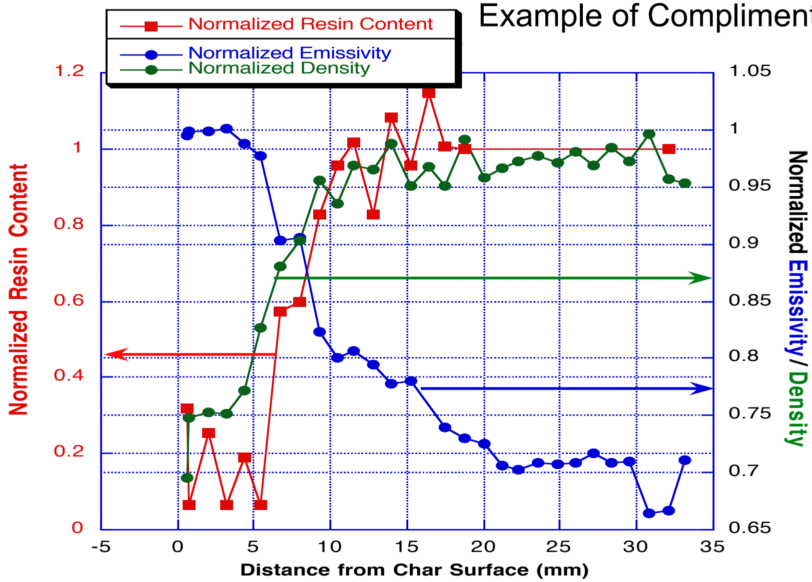


Location	Measured Recession cm (inch)	Calculated Recession cm (inch)	Percent Difference (+ve is overprediction of recession)
Stagnation Point	*	1.1 (0.43)	
Near - Stagnation Core 1	0.57 (0.22)	0.97 (0.33)	+70%
Flank Core 2	0.32 (0.126)	0.38 (0.13)	+19%

Ongoing Evaluations and Some Key Observations

Stardust Post-flight Analysis

Example of Complimentary Analysis Completed on Near Stagnation Core



- Emissivity measurements capture a change in the material vs location that is not picked up in density or resin content measurements

Ongoing Efforts to Support Ground to Flight Traceability

- Chemical analysis vs location
  - Supports airborne observation and differences picked up in emissivity data
- Microprobe laser-desorption laser-ionization mass spectrometry analysis
  - Support ground to flight traceability (compositional)
- Coupled UV and spectroscopic techniques
  - Determine heating history experienced by cores (Stardust was not instrumented)
- Thermal properties
  - Thermal conductivity (input for thermal response model)
- Strength of Stardust remaining virgin PICA
  - Comparable to heritage

PICA Observations

- Heatshield in excellent condition overall
- Recession over-predicted
- Char depth over-predicted
  - "char" considered to be region where density less than virgin
  - FIAT/PAT density profile shows slope change in char region not seen in measured data
    - result of reaction model
- FIAT/PAT predicts less char-depth for stagnation core 1 than flank core 2
  - Measured density profiles show similar trend
- Measured density shows surface layer of low density as compared to calculation
  - Due to elimination of high surface area phenolic char phase

Summary

- Post-flight analysis of Stardust SRC focusing on tasks most useful to CEV
  - PICA forebody heatshield is current primary emphasis
- Leveraging airborne observation data, radar, and recovered hardware
- So far, seeing reasonable correspondence between analysis and available data

Future Work

- Fully-coupled flowfield material response
  - simulate heatshield ablation products in flowfield
    - compare to observation data (CN lines)
  - simulate thermal control paint ablation products in flowfield
    - compare to observation data (Potassium and Zinc lines)
    - need a paint ablation model
- Examination of edge slice
  - opportunity for multi-dimensional material response model assessment
- Further examination of air emission lines

NASA Funding

- CEV TPS Advanced Development Project
- NASA Engineering and Safety Center
- Fundamental Aeronautics Program

Detailed technical reports to be presented:

AIAA Aerosciences Meeting and Exhibit
Reno, NV
January 2008

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