Integrated Thermal Vacuum Testing of the Solar Array Cooling System for Parker Solar Probe

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Presented By
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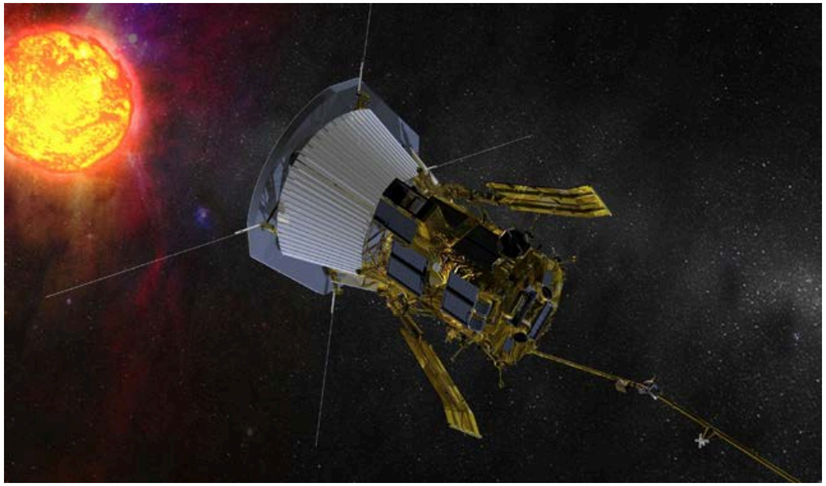
Parker Solar Probe Mission Summary



Overview

Using in-situ measurements made closer to the Sun than by any previous spacecraft, Parker Solar Probe (PSP) will determine the mechanisms that produce the fast and slow solar winds, coronal heating, and the transport of energetic particles.

PSP will fly to less than 10 solar radii (Rs) of the Sun, having "walked in" from 35.7 Rs over 24 orbits.

Sponsor: NASA SMD/Heliophysics Div

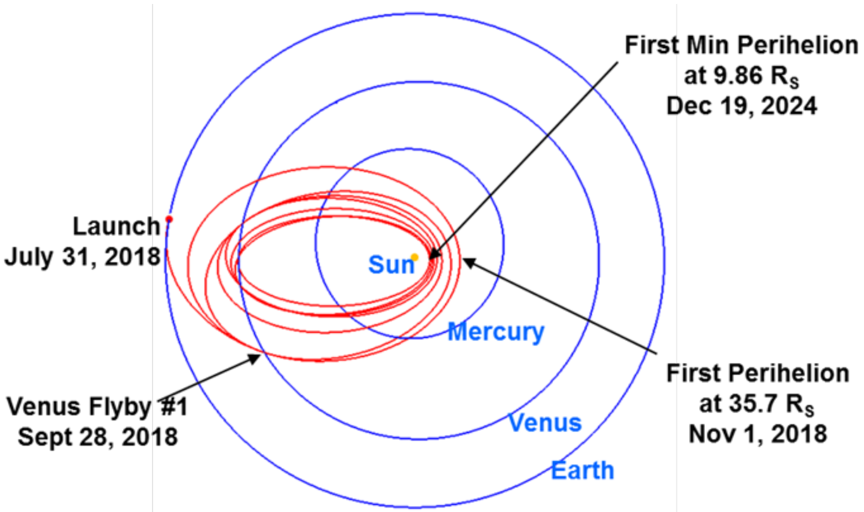
- **Program Office – GSFC/LWS**
- **Project Scientist - APL**
- **Project Management - APL**
- **S/C Development & Operations – APL**
- **Science Investigations selected by AO:**
  - **SWEAP - Smithsonian Astrophysical Observatory**
  - **FIELDS - UC Berkeley**
  - **WISPR - Naval Research Laboratory**
  - **ISIS – Southwest Research Institute**
  - **HelioOrigins – Jet Propulsion Laboratory**

Preliminary Mission Milestones (Assuming 2018 Launch)

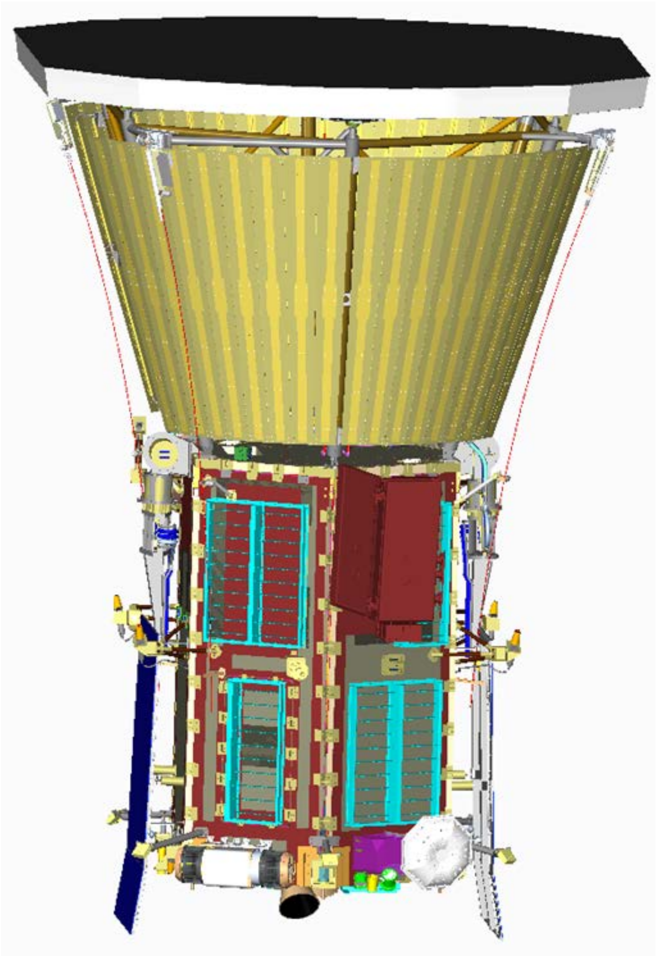
Pre-Phase A:	**07/2008 – 11/2009**
Phase A:	**12/2009 – 01/2012**
Phase B:	**02/2012 – 03/2014**
Phase C/D:	**03/2014 – 08/2018**
Phase E:	**09/2018 – 09/2025**

Trajectory: 9.86Rs Minimum Perihelion

- Launch
  - 12-day launch period from Aug 11 to Aug 23, 2018
    - Launched on 12 August @ 03:31 EDT
  - Maximum launch C3 of 154 km2/s2
  - S/C wet mass 685 kg
  - Launch system: Delta-IVH Class + Star48 BV
- Mission Trajectory
  - A V7GA type of trajectory requiring 7 Venus gravity assist flybys
  - No deterministic deep space maneuvers
  - Consisting of 24 solar orbits, 3 has minimum perihelion
  - Perihelion gradually decreasing to 9.86 RS
- Final Solar Orbit
  - Perihelion of 9.86 RS
  - Aphelion of 0.73 AU
  - Orbit inclination of 3.4 deg from ecliptic
  - Orbit period of 88 days
- Mission Timeline
  - Launch to 1st perihelion: 3 months
  - Launch to 1st min perihelion (9.86 RS): 6.4 years
  - Mission duration (including 3 passes at 9.86 RS): 7 years

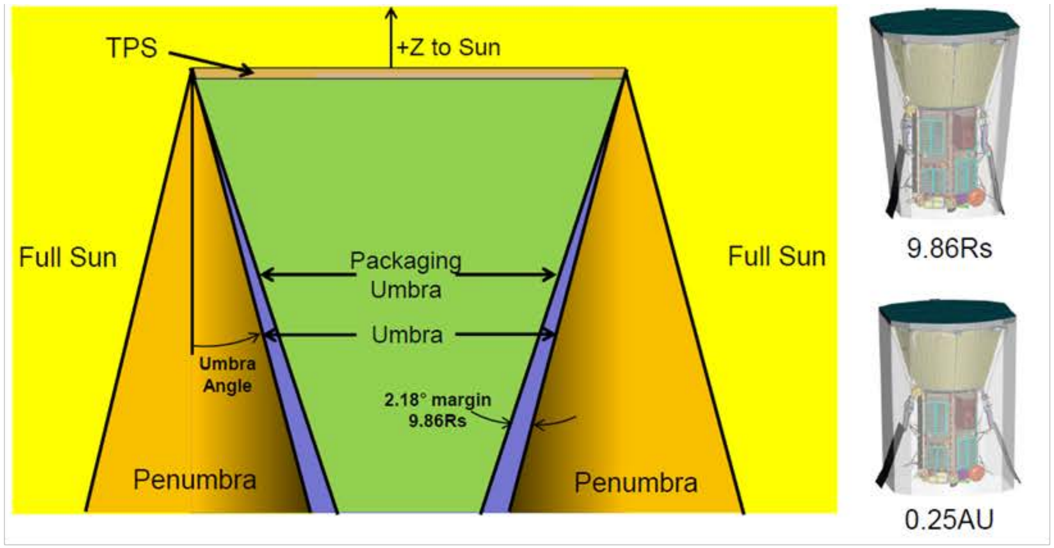


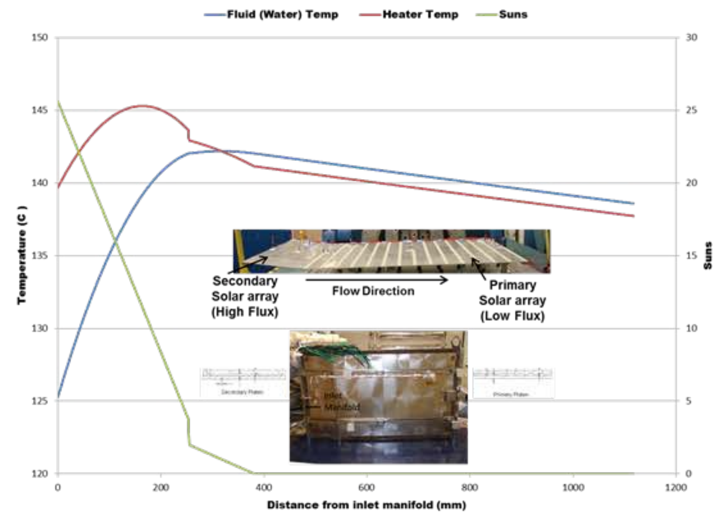
Spacecraft Overview



- NASA selected instrument suites
- 685kg max launch wet mass
- Reference Dimensions:
  - S/C height: 3m
  - TPS max diameter:2.3m
  - S/C bus diameter: 1m
- C-C Thermal protection system
- Hexagonal prism s/c bus configuration
- Active, water cooled solar arrays (SA)
  - 364W (TBR) electrical power at encounter
  - Solar array total area: 1.54m^2
  - Radiator area under TPS: 4.0m^2
- 0.6m HGA, 34W TWTA Ka-band science DL
- Science downlink rate: 163kb/s (TBR) at 1AU

Concentrated heat loading requires active solar array thermal control



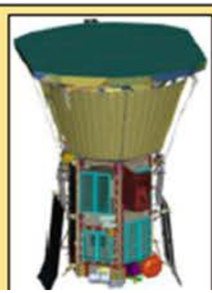


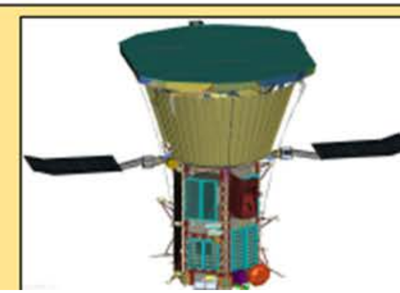
9.86 Rs (~26 suns)

54 Rs (~ 6 suns)

150 Rs (~ 2 suns)

Solar Array Position





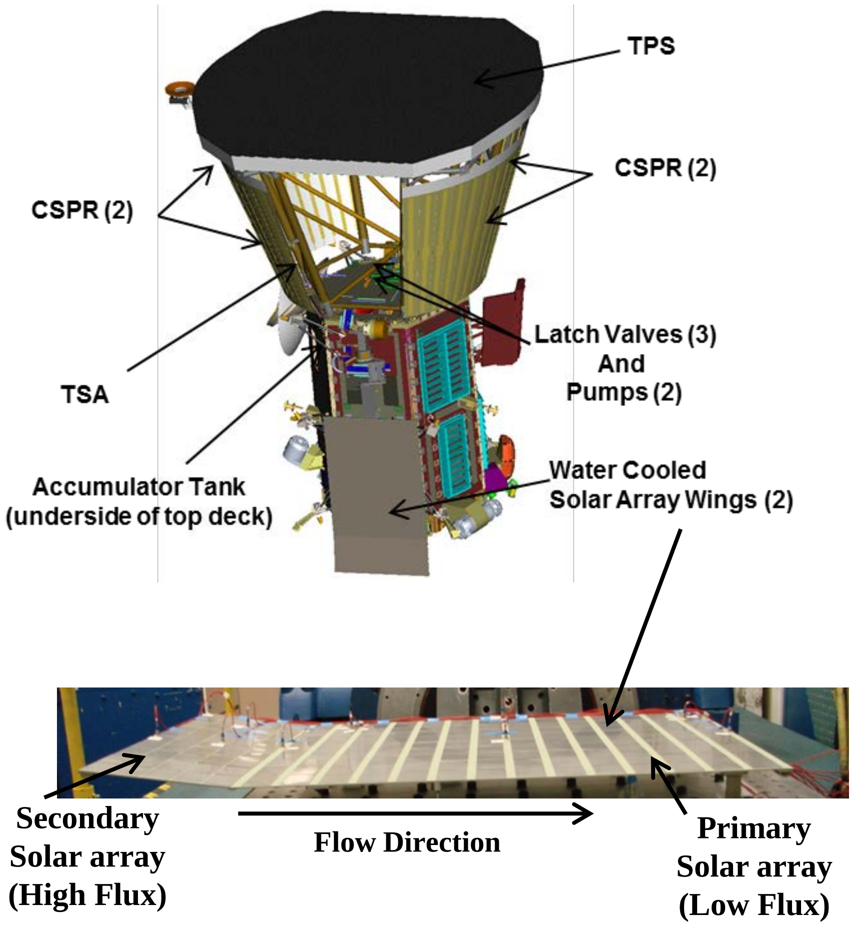
Solar Array Cooling System (SACS)

- PSP liquid cooling system dissipates high solar flux absorbed by solar array during closest approach to sun
  - Designed for 6400 W cooling system capacity at 9.86Rs
- Water pumped through solar array wings into cooling system primary radiators (CSPR) to dissipate heat.
- Single loop, redundant pump and control electronics
- Cooling system operating temperature determined by solar distance, spacecraft pointing, solar array angle, pump speed (2 speed)
  - Operating temp: +20C to +150C
  - Survival temp: +10C to +190C
  - Survival dry: platen: -80C, CSPR: -130C
- Thermal design drivers

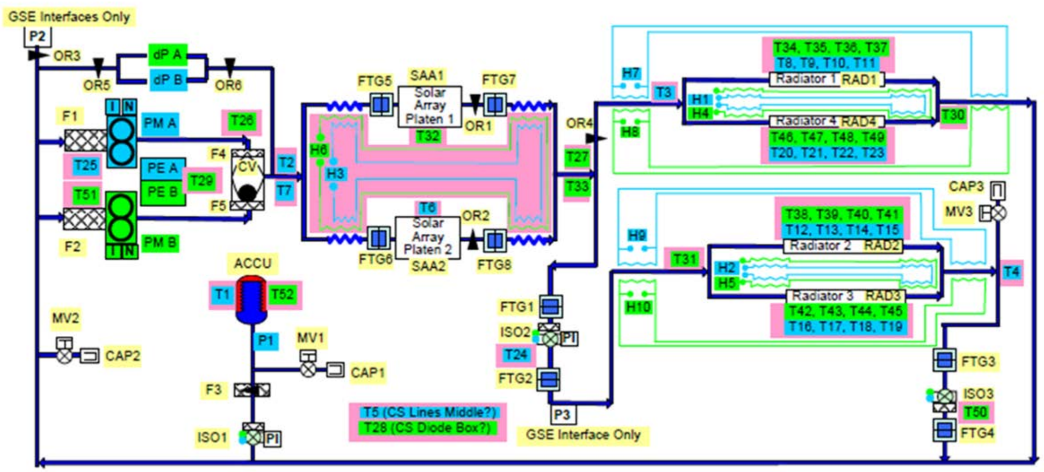
Hot (SS)
- 9.86Rs – max cooling system load (4AR)
- Communication 45deg slews (4AR)

Cold (SS)
- 0.82 AU Umbra (4AR) / 1.02AU (2AR & 4AR)

Cold (Tran)
- Venus eclipse
- Launch, post launch activation
- R23 Activation (L+41)



SACS Activation and Operation



Key System Components

- Accumulator – not redundant
- Pump and Pump Electronics – block redundant
- Solar Array Platens/Cold Plates – not redundant
- Radiators – not redundant
- Isolation Valves – electrically redundant/cross strappe
- Delta Pressure Sensors – redundant/cross strapped

- Launch to Cooling System Activation ~two hours total:
  - **Before launch, water in the accumulator is heated by an external UGSE heater to a temperature between 40° C to 50° C to overcome any cold spots in the radiators and tubing and assure the system does not freeze when it is initially wetted**
- Activation of cooling system radiators 2 and 3 occurs at solar distance 0.89-0.9AU (~Day 41 / Launch Correction Maneuver completed)
  - Spacecraft slew to "Activate 2&3" pointing orientation
  - Radiator 2&3 warm up to 20C prior to opening valves to flow water through radiators 2&3
  - Ground command sequence

Transient

Name	View from Sun	Solar Distance	Duration
Activate Radiators 1 and 4		1.02 AU	~ 1 hr
Activate Radiators 2 and 3		0.9 AU to 0.89 AU	< 1 hr

Steady State

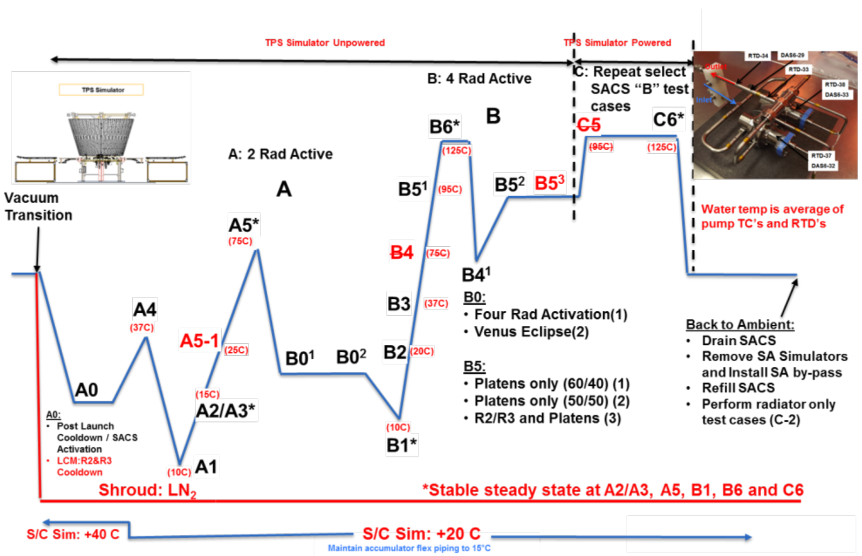
Solar Distance	Description / View from Sun
1.02 AU to 0.82 AU	Aphelion
0.82 AU to 0.7 AU	Aphelion-Umbra Variable
0.7 AU to 9.86Rs	Umbra/ Encounter

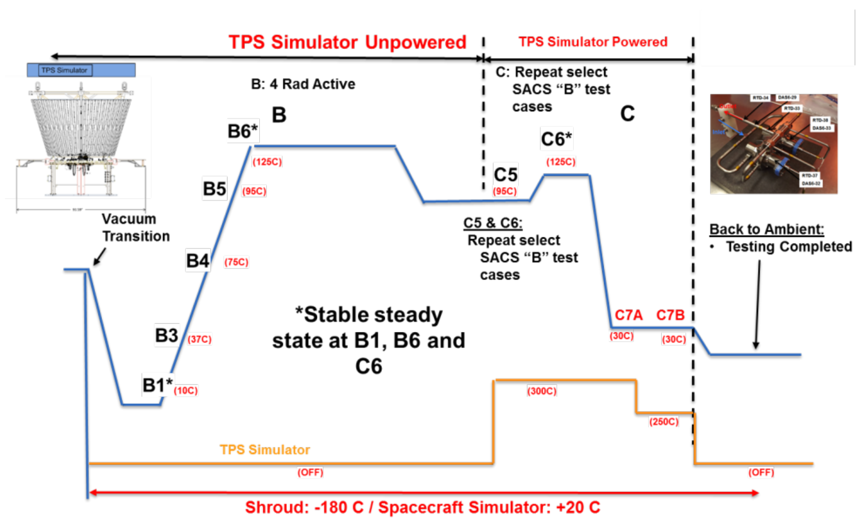
Design Verification

- During ITVT, the thermal performance of the SACS was evaluated using test configuration 1 (C-1) (test platens installed/total system AE) and test configuration 2 (C-2) (test platens removed), which were designed to bracket the entire mission phases expected during flight, including the critical transients.
    - C-1 Cold Case A2: Measure Steady Temperature with two radiators active and compare against expected heat loading 933 W to verify fin blanketing and to determine if additional mli is needed. This configuration dictates fin mli sizing due to expected worst case SA waste heat at 1.02 AU (933 W)
    - C-1 Cold Case B2: Measure Steady Power at 15 C with four radiators active with fin mli in place. This case determines the minimum four active radiator heat load and quantifies R23 slewing during flight operations
    - C-1 Hot Case B6 (No TPS): Quantify SACS EOL capacity at 125 C with fin MLI in place. Defines the new required capacity (spec/no fin mli is 6400 W)
    - C-2 Hot Case B6 (No TPS): Quantify the SACS power at 125 C without patens
    - C-2 Hot Case C6 (TPS @ 300 C): Quantify the SACS power at 125 C. The difference from the previous case is the TPS loading into the SACS
    - C-1 Critical transient simulation Cases A0, $B0^1$, $B0^2$: Post launch warm up, R23 activation and Venus eclipse. All used as predicted worst case heat loads
- Intermediate C-1 & C-2 cases were used to provide SACS hydraulic system performance over temperature, flow rate and active radiator configuration, and provide temperature and power data for the thermal model correlation
- Testing verified the thermal performance of the SACS during steady-state and critical transient operational scenarios. The testing also directly measured the heat flow from the TPS into the SACS radiators and into the spacecraft top deck (via the spacecraft simulator)

Test Profiles

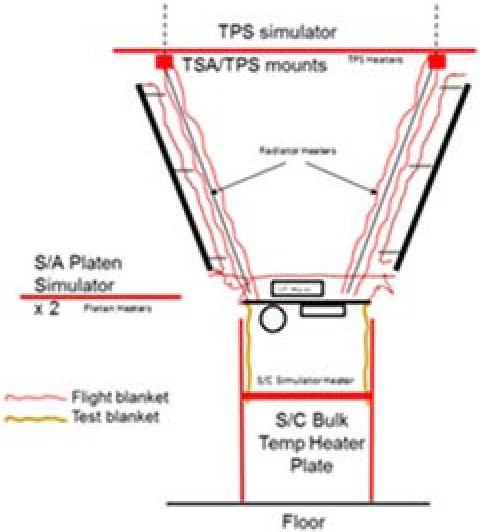
- The flight configuration, C-1, was used to verify critical thermal requirements and characterize system performance as a function of temperature and water flow rate for both the two and four active radiator configurations with the equivalent of two radiator fins per radiator blanketed on radiators 1 and 4. This configuration was also used to demonstrate solar-array-related autonomy responses to heat flux and verify acceptable performance during the critical transients.
- The non-flight autonomy and fault protection configuration, C-2, represents the configuration that was used during observatory testing to allow free motion of the solar-array gimbals to verify fault protection and solar array safing response to anomalous thermal conditions that were simulated during test. The data gathered during ITVT was used to help set the operating SACS parameters. All SACS thermal control (heating) was done using the four radiators in a symmetric manor

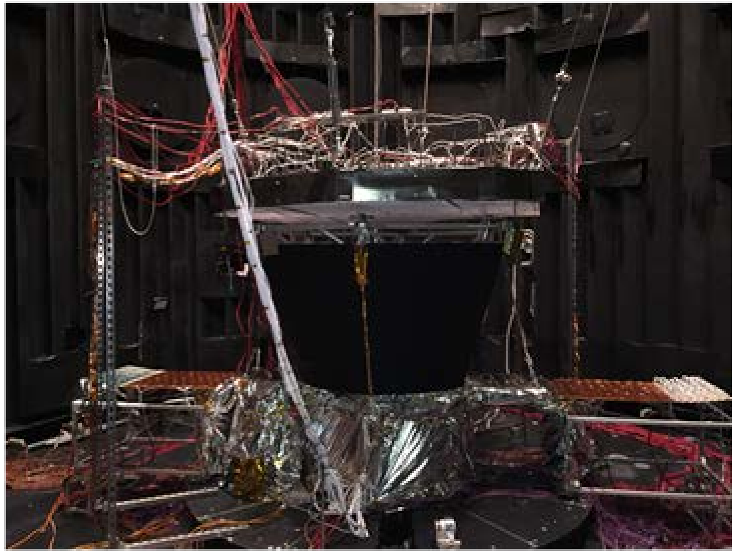




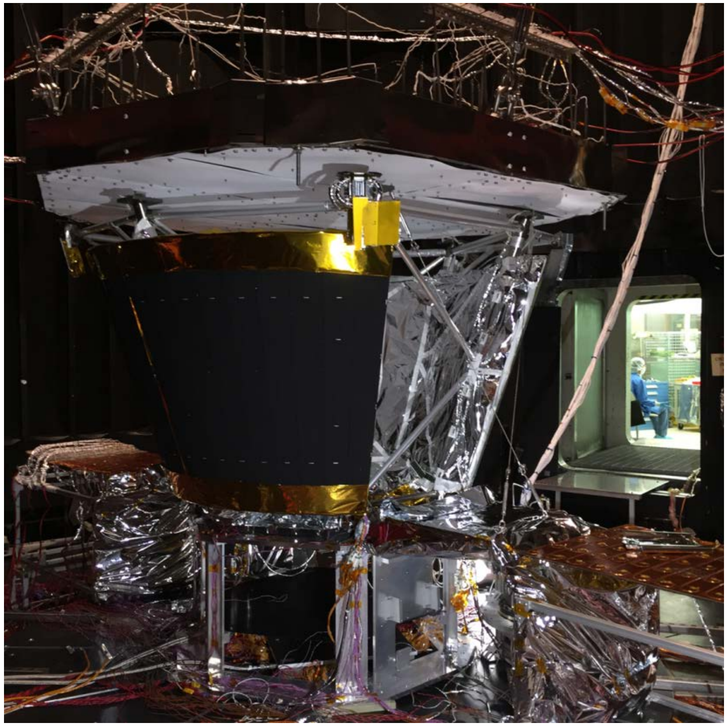
Test Setup

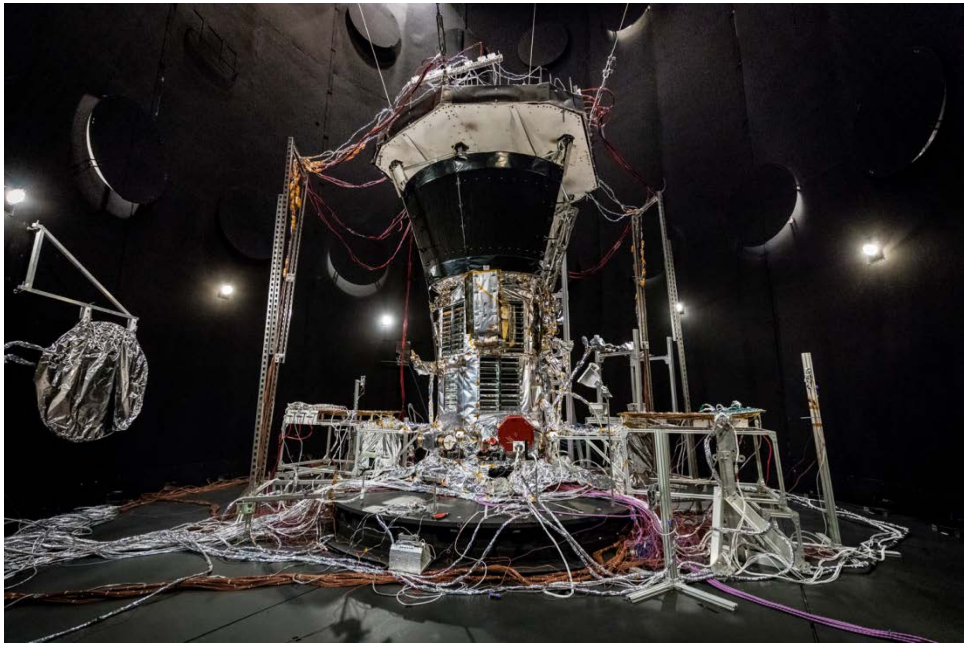
- The ITVT article consisted of both actual flight and non-flight hardware elements. Actual flight hardware evaluated during the ground test consisted of the radiators, the radiator heaters (included for the ground test but not used in flight), the TSA, and the cooling water supply system.
- Electric heaters were used to emulate various PSP mission environments. These heaters were energized by a combination of high-power (100 V/50 A) and low-power (60 V/5 A) supplies. Low-power heaters were used to provide energy to the radiator panels, the spacecraft simulator, the solar-array boom heater, the plumbing electronics box, and the water connection lines. A combination of low- and high-power heaters were used to warm the platens.
- Additionally, high-power heaters were used to provide energy to the TPS thermal simulator. The TPS thermal simulator provided back-side temperatures in the range of 300° C to 350° C.





Test Configuration 1 (GSFC SES290)

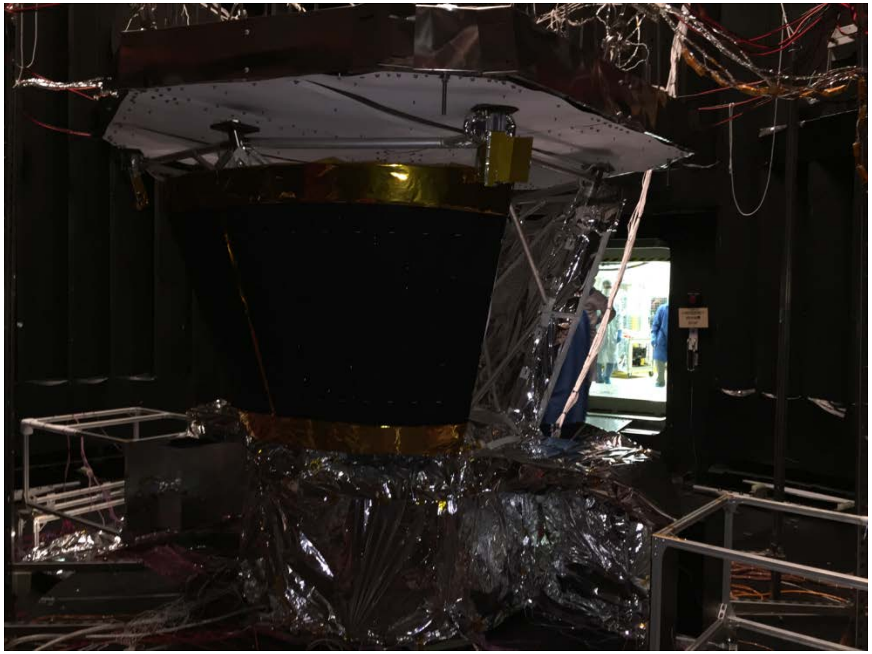




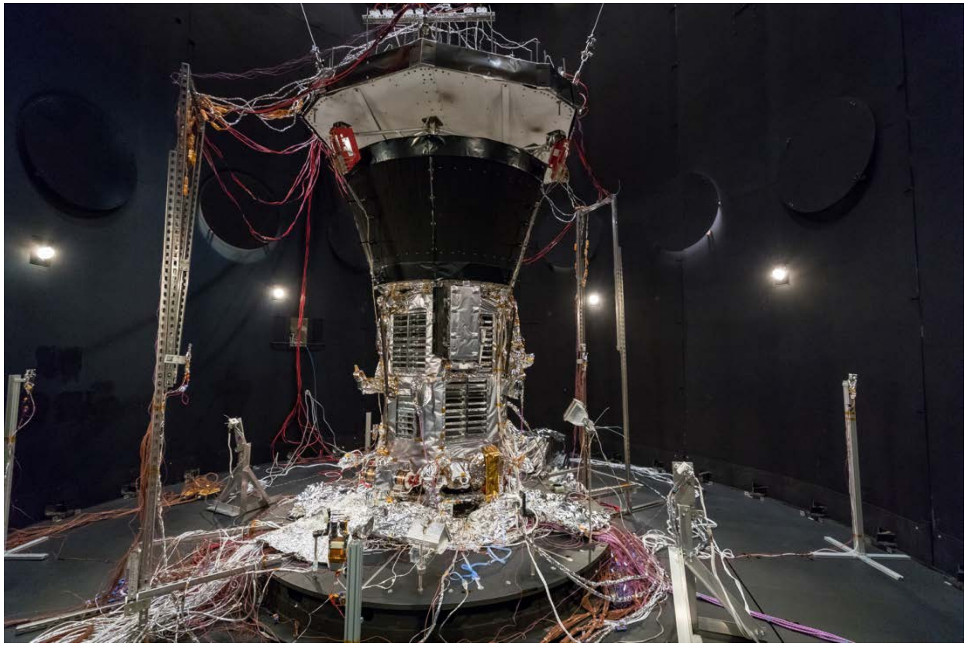
ITVT C-1 Fin MLI is visible

Observatory C-1 Fin MLI is visible

Test Configuration 2



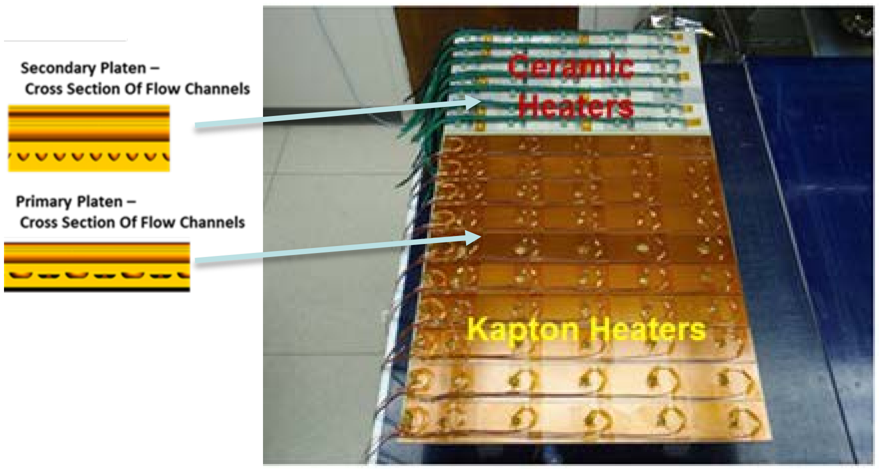
ITVT C-2 Fin MLI is visible



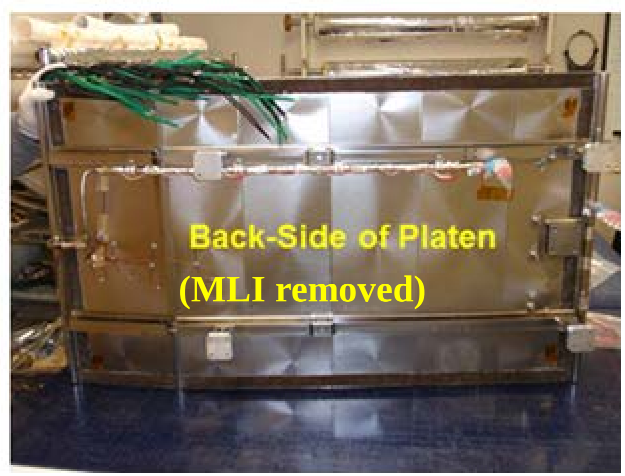
Observatory C-2 Fin MLI is visible

Special GSE: Test Platens

- To properly simulate the high-intensity solar load experienced by the flight solar arrays, the test platens were heated using a combination of ceramic heaters in high-heat-flux areas (the angled platen areas) and Kapton heaters in low-heat-flux regions
- The test and flight solar-array platens are fabricated from diffusion bonded CP Grade-4 titanium and utilize identical internal mini-channels geometry to collect the waste heat from the solar cells (or heaters). The mini-channel design is different for the secondary and primary segments to minimize pressure drop during maximum flow.
- The short secondary segment (254 mm in length) uses a small-diameter densely packed mini-channel design that efficiently removes the waste heat when at the highest flux; however, this comes with a pressure-drop penalty. To reduce the pressure-drop penalty, the primary segment (864 mm in length) transitions to a larger-diameter mini-channel design, in the region of the plane change, because the heat flux profile is very benign and the pressure drop would be more substantial due to the greater length.
- For transient considerations, the mass of the test platens matches the as-built mass of the flight solar arrays to within 1%. As reference, the test and flight platens are uniform in width, measuring 635 mm and 686 mm, respectively, and both are 1118 mm in length.

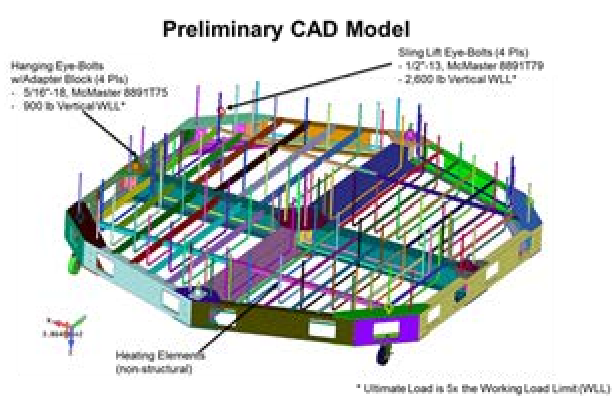


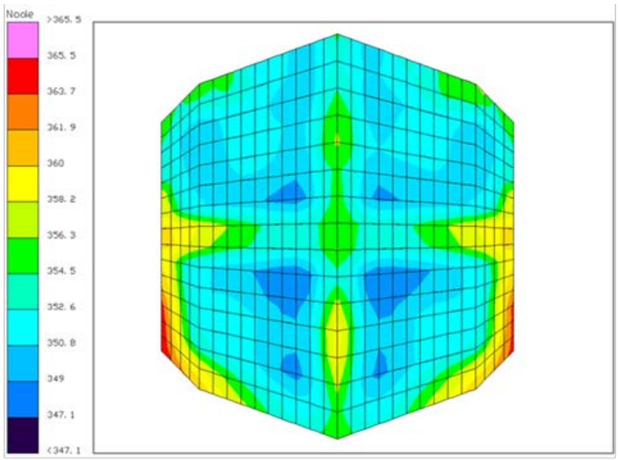
Mass=18.5 kg



Special GSE: TPS Simulator

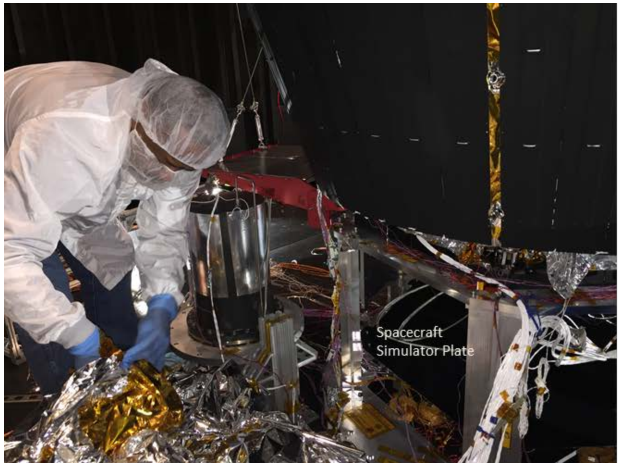
- Approximately 90” in diameter, the flight TPS points toward the sun during closest solar approach, and shields the spacecraft bus from direct solar impingement.
- In flight the top (i.e., sun-facing) surface of the TPS is predicted to reach temperatures in excess of 1200˚ C. The bottom (i.e., bus-facing) surface of the TPS is predicted to reach temperatures near 300˚ C, creating an important source of incident infrared heating on the bus.
- The thermal simulator was designed to provide the critical environments expected during flight when the TPS is both hot and cold.
- Heat back loading into both the SACS and bus were quantified during the ITVT and was repeated during final spacecraft thermal vacuum testing , verifying that the spacecraft thermal design could manage infrared heat load.

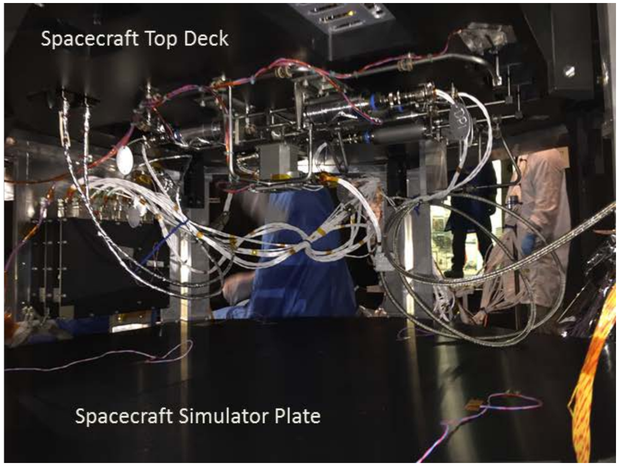


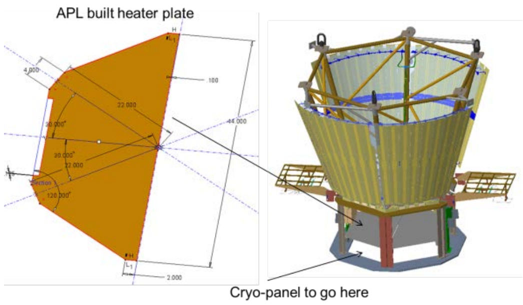


Special GSE: Spacecraft Simulator

- The spacecraft simulator utilized two plates, with ten Kapton heaters per plate to measure the heat leak into the simulated spacecraft bus from the SACS and TPS simulator.
- The simulated spacecraft boundary condition of 20° C was held for both test configurations (C-1 or C-2), and the power needed to maintain this temperature setting was measured.
- As the SACS and TPS simulator warmed, the conducted and radiated heat caused the input power needed by the spacecraft simulator to decrease.
- Delta changes in control heater power needed to maintain 20° C on the plates provided direct measurements of heat flow into the underlying structure.

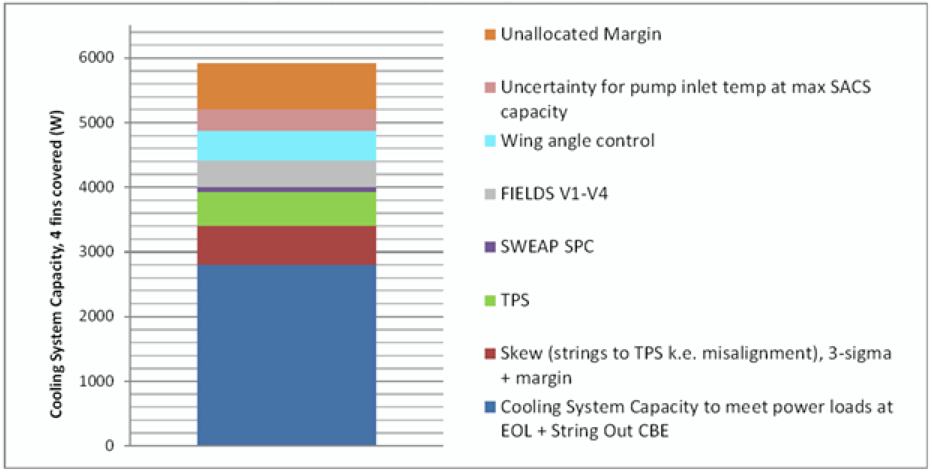






Test Summary

- **C-1 Cold Case A2: From the results, for 934 W of thermal input, the SACS water temperature was measured to be 14° C. Because the desired water temperature is~18° C with 933 W of thermal input, the MLI coverage will be increased to 0.63 m^2 based on the correlated thermal model**
- **C-1 Cold Case B2: From the results , for 1720 W of thermal input, the SACS water temperature was measured to be 19° C**
- **C-1 Hot Case B6 (No TPS): From the results, for 6153 W of thermal input, the SACS water temperature was measured to be 125° C (spec/no fin mli is 6400 W) and pre-test budget carried 5900 W as the max capacity**
- **C-2 Hot Case B6 (No TPS): 4612 W / 125 C SACS**
- **C-2 Hot Case C6 (TPS @ 300 C): 4037 W / 124 C SACS (300 C TPS simulator); Heat flow into SACS from TPS measured to be 575 W (533 W estimated in the budget)**
- **C-1 Critical transient simulation Cases A0, B0[1], B0[2]: All critical transients were nominal and without any issues.**



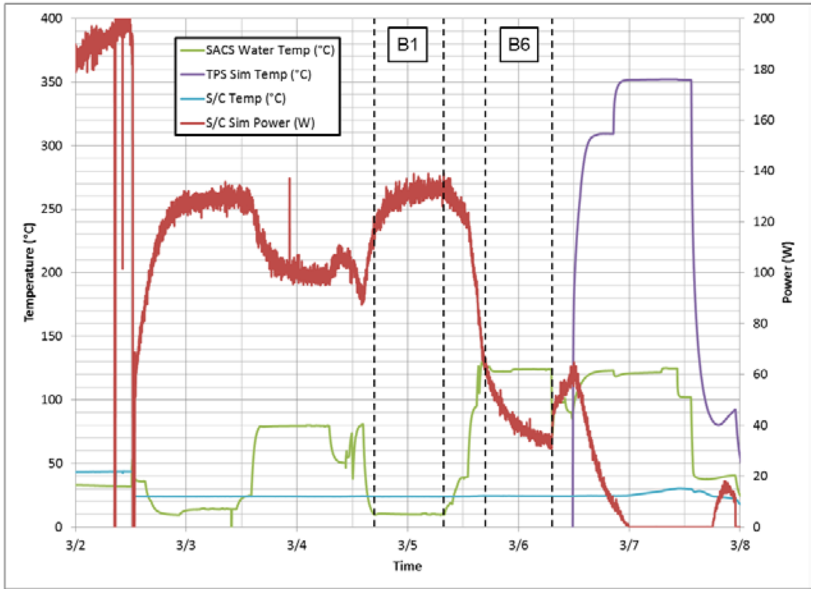
The SACS pre-test thermal budget

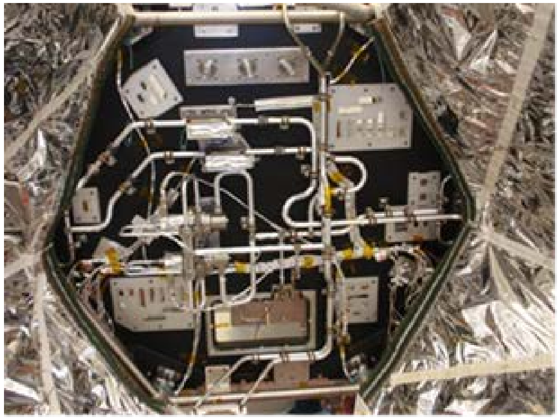
Test Anomaly: SACS Excessive Heat Leak

- During C-1/B6, it was very apparent that the heat from the SACS into the spacecraft simulator with the SACS at 125° C was much higher than expected. Upon analysis of the test data, the effective leak into the spacecraft simulator was measured to be grossly 100 W, approximately three times greater than that expected from the pretest thermal modeling.
- It was determined that the majority of the unexpected heat leak was due to much higher thermal conductivity in the component mounting hardware, which, in turn, caused the underside of the top deck to become considerably warmer and radiate three times the expected heat into the spacecraft simulator.
- The design fix, successfully verified during observatory-level thermal vacuum testing, was to add an MLI blanket between the underside SACS components (keeping them radiation coupled to the internal spacecraft) and the underside of the top deck to isolate the top deck from the inside of the spacecraft.
- Black Kapton tape was also added to the underside components to increase the surface emissivity and help with thermally coupling these components to the spacecraft bulk temperature

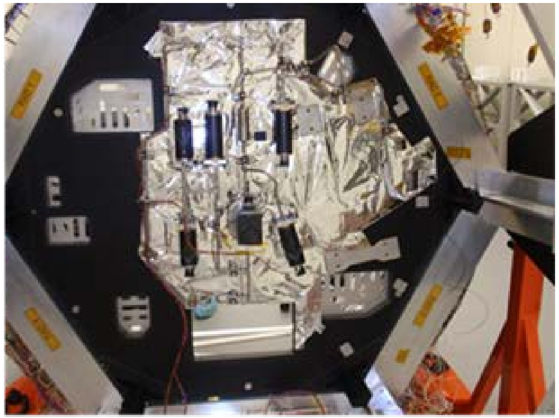
SACS Excessive Heat Leak Data and Fix

- **B1:**
  - **SACS Temp 10°C**
  - **S/C Sim Power 133 W**
- **B6:**
  - **SACS Temp 124°C**
  - **S/C Sim Power 34W**





Top Side of Top Deck final configuration
(Faces toward TPS)

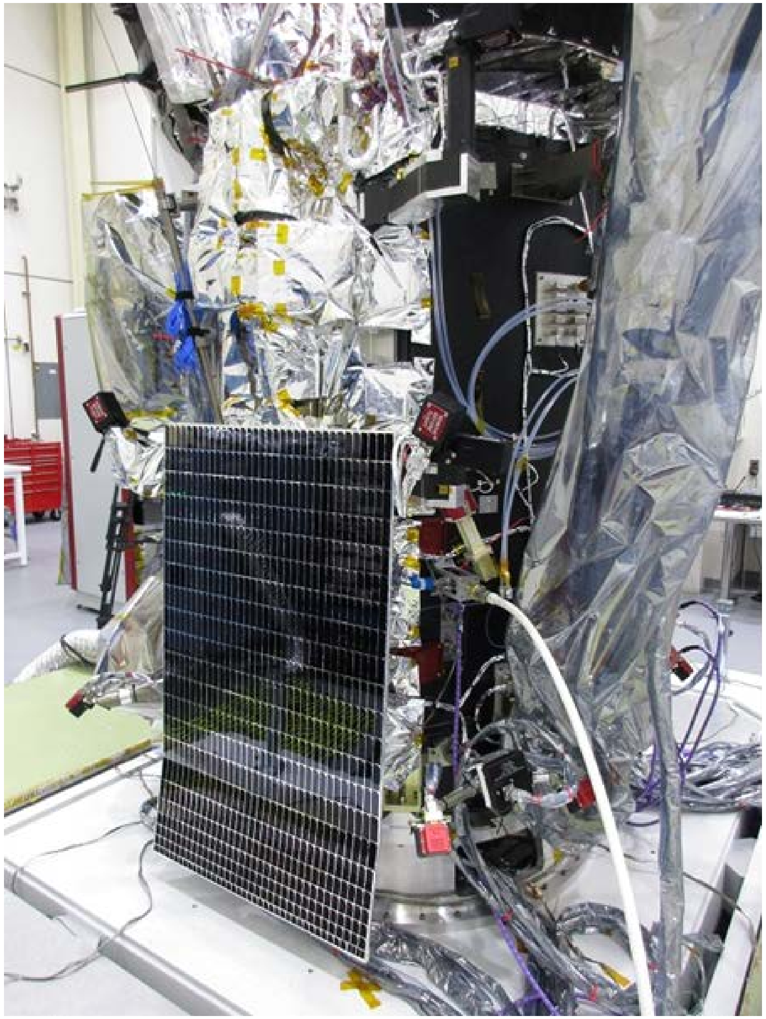


Underside of Top Deck with partial MLI installed
(Faces toward inside of spacecraft)

Conclusions

- The successful ITVT provided verification that the SACS subsystem performed as expected over a broad range of active radiators, temperatures, input power, and transient responses, both thermal and electrical.
- The test helped to close a majority of the Level 4 requirements that were based on hot and cold system performance with two and four active radiators, hot and cold expected heat loads, and the aggregate system time constant.
- The test provided an end-to-end functional test that allowed all of the flight hardware to be integrated and operated together over a wide range of temperatures, radiator configurations, and pump speeds
- The design flaw regarding anomalous top-deck heat leak was unambiguously exposed and quantified, and a simple fix was implemented before SACS integration. Without performing an "integrated thermal test" where the spacecraft was thermally represented by the simulator plate, this problem would not have been found until the observatory-level thermal vacuum test, and implementing the fix would have been an enormous undertaking from a technical and schedule perspective

Solar Array Launch Configuration and SA Boom articulation



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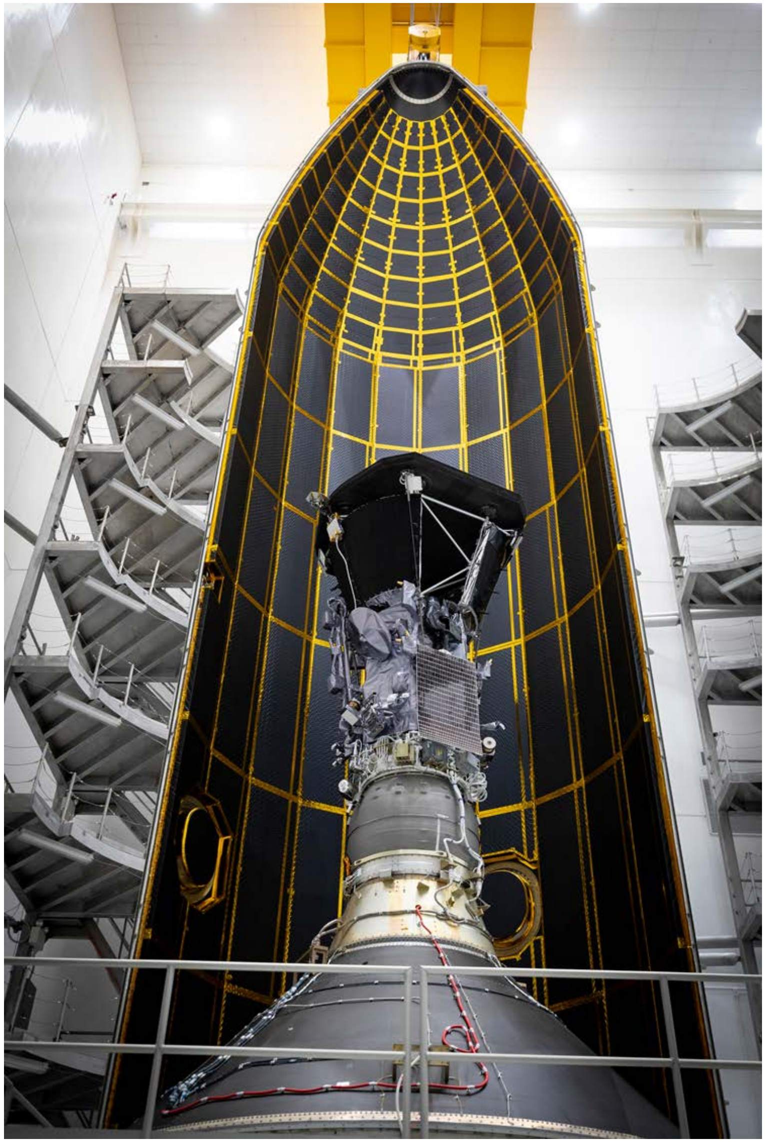
- **The SACS was manufactured by Hamilton Sundstrand, Windsor Locks, CT, who continue to support engineering operations**

The Blanket Team

Tony Ahan, Lynsey Gwilliam, Neal Bachtell, Eric Wallis, Helen O'Conner, Jen Fischer

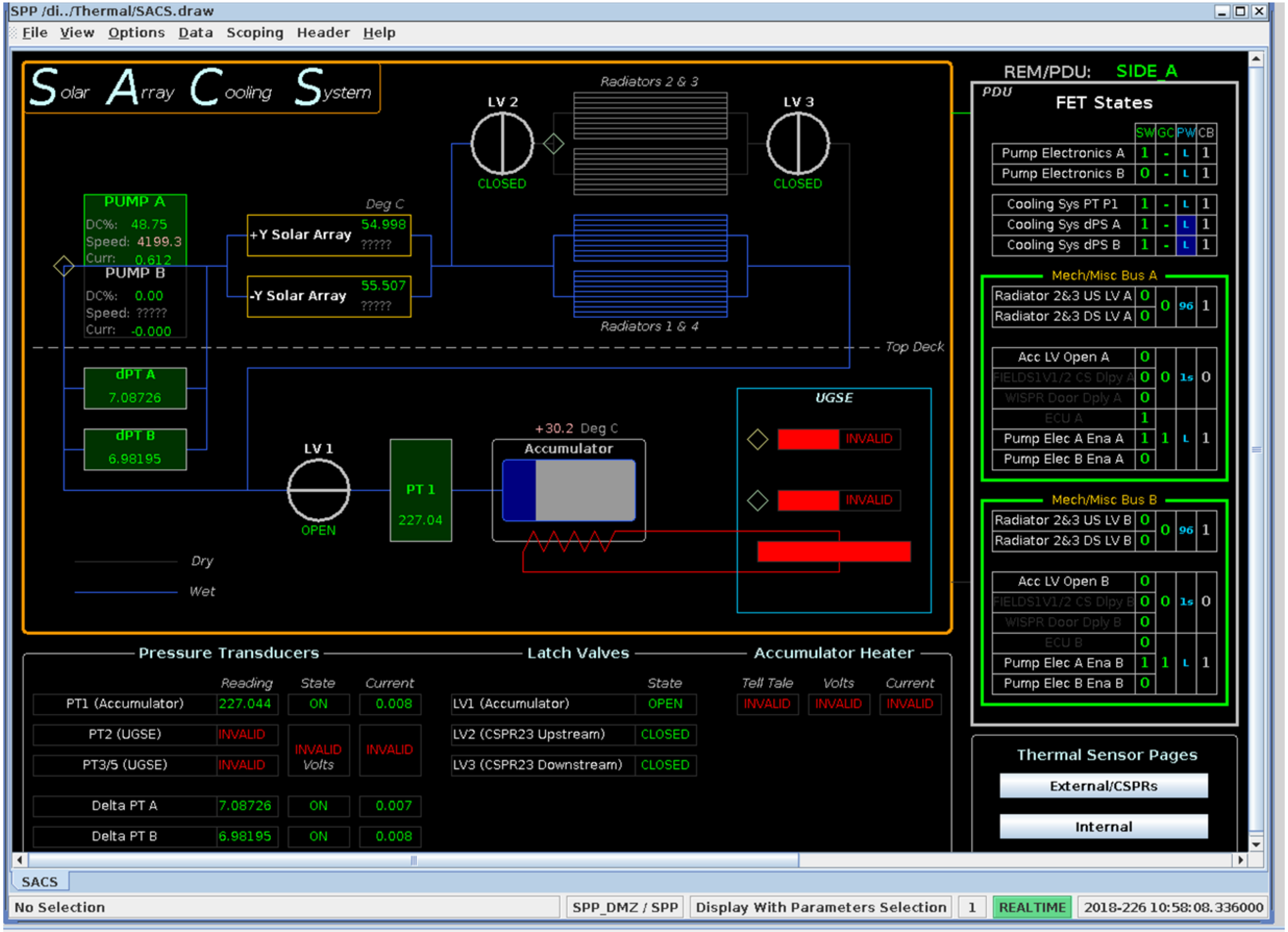
PSP One Day Prior to Full Encapsulation



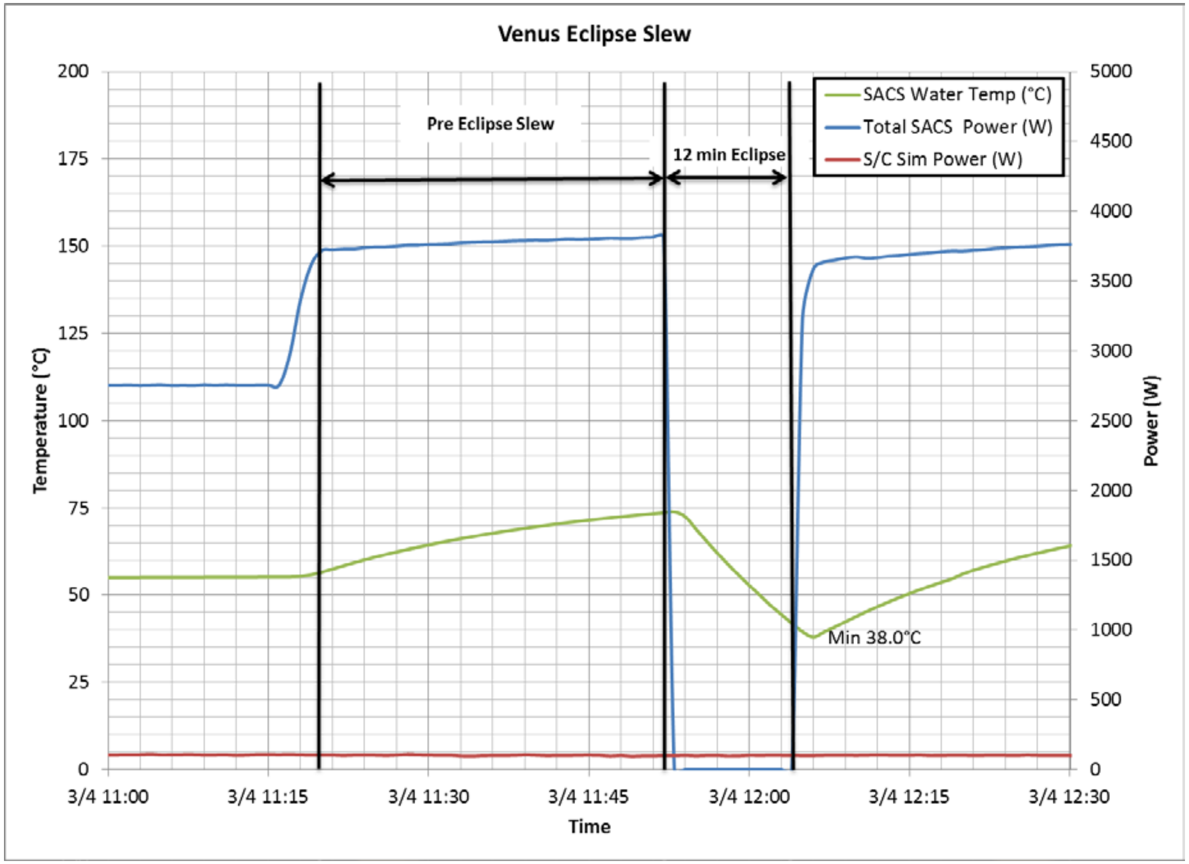
Ready to Go

12 August @ 03:31 EDT

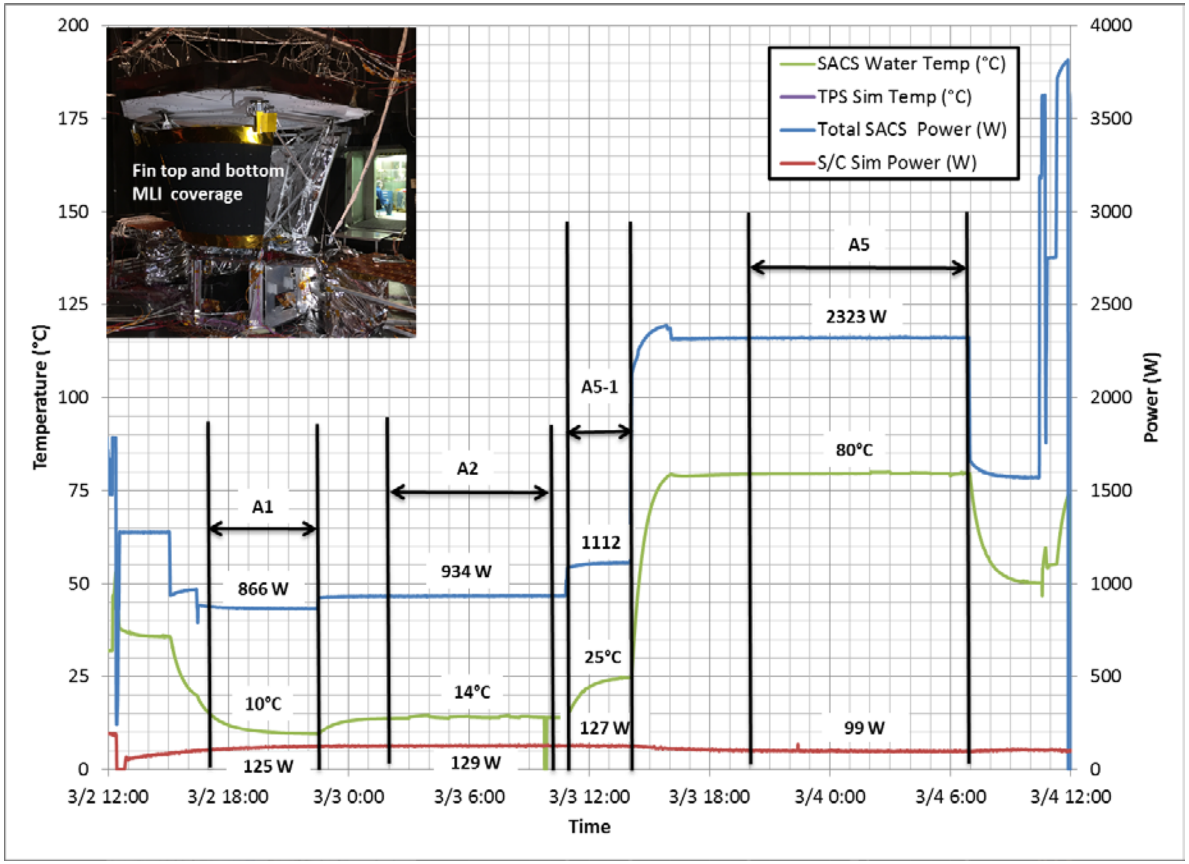
SACS HL ~1700 W (Day 3)



Back Up Venus Eclipse Transient

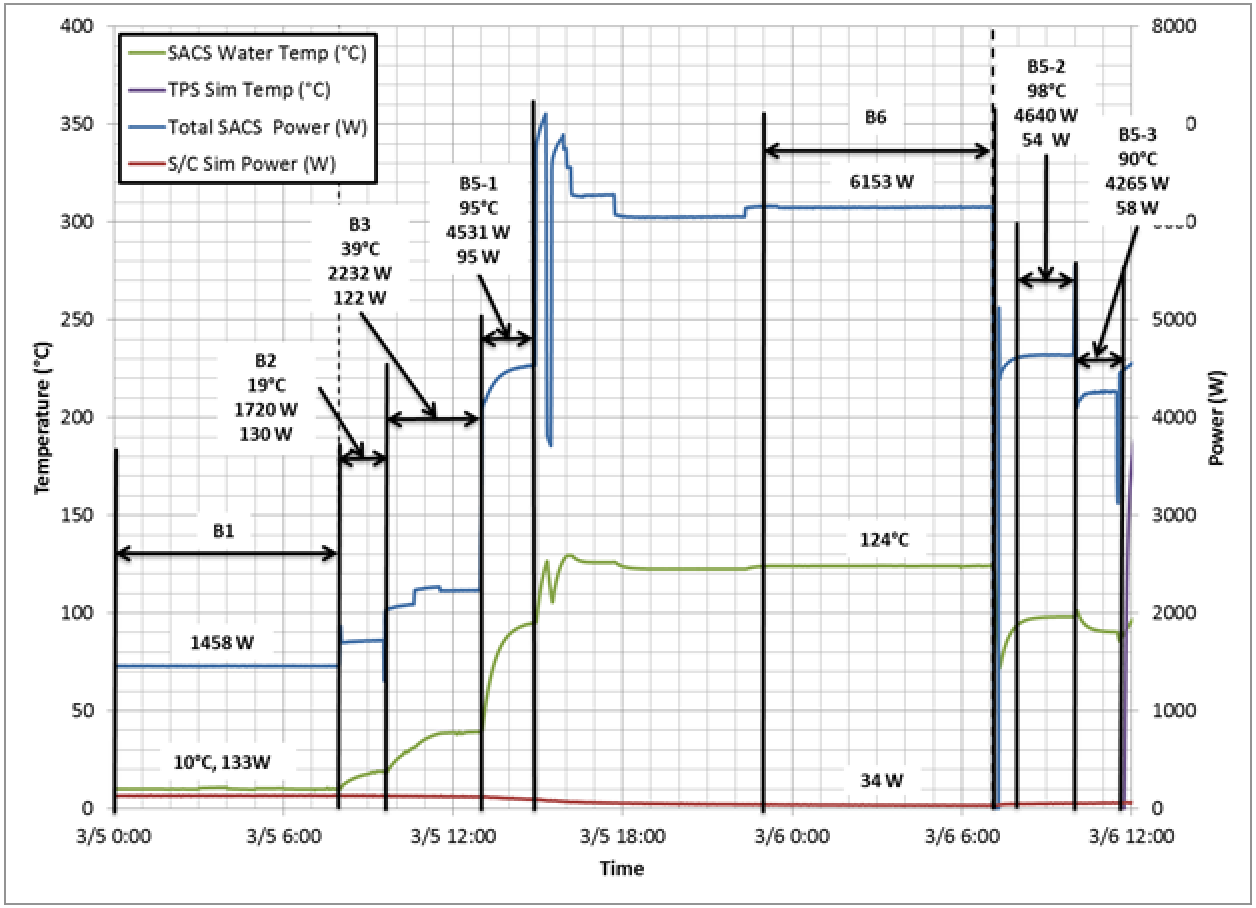


Back Up C-1 / A



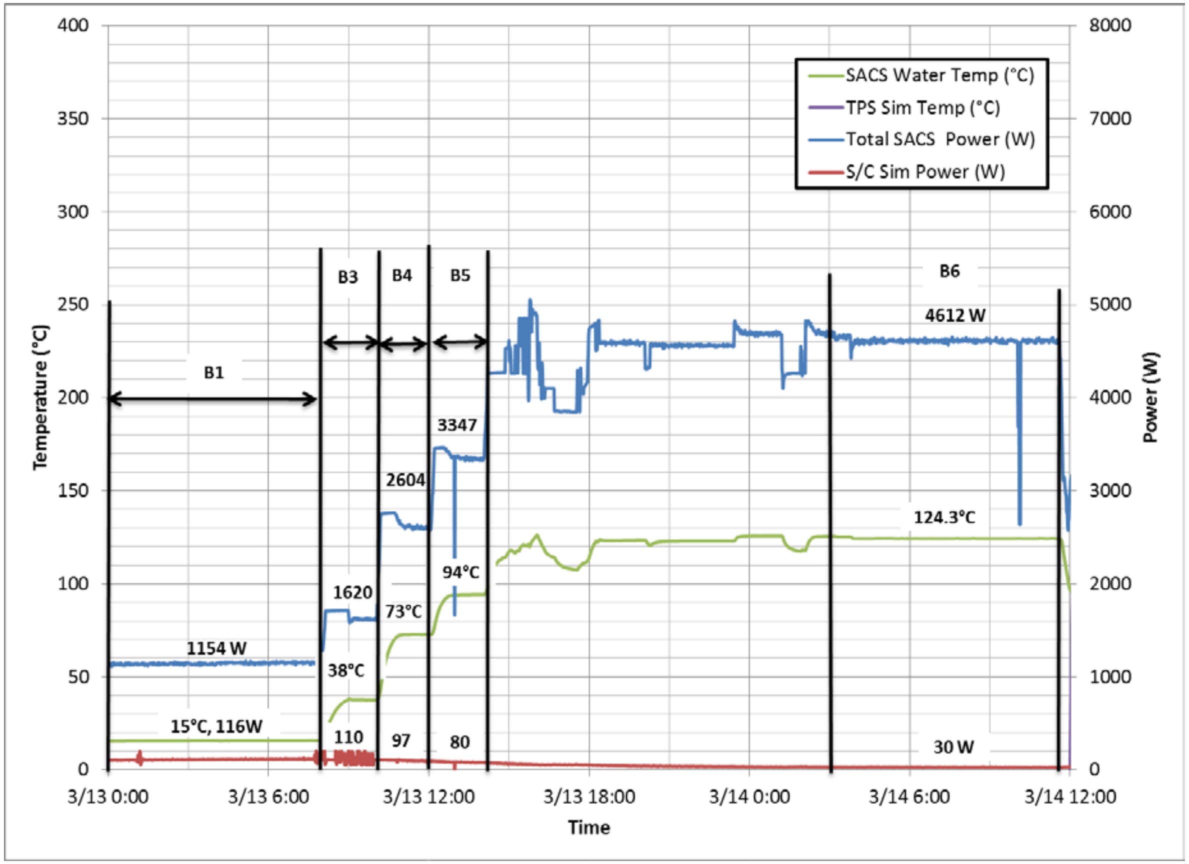
Fin top and bottom MLI coverage
SACS Water Temp (°C)
TPS Sim Temp (°C)
Total SACS Power (W)
S/C Sim Power (W)
A1
A2
A5-1
A5
866 W
934 W
1112
2323 W
10°C
14°C
25°C
80°C
125 W
129 W
127 W
99 W
Temperature (°C)
Power (W)
Time
0
25
50
75
100
125
150
175
200
500
1000
1500
2000
2500
3000
3500
4000
3/2 12:00
3/2 18:00
3/3 0:00
3/3 6:00
3/3 12:00
3/3 18:00
3/4 0:00
3/4 6:00
3/4 12:00

Back Up C-1 / B



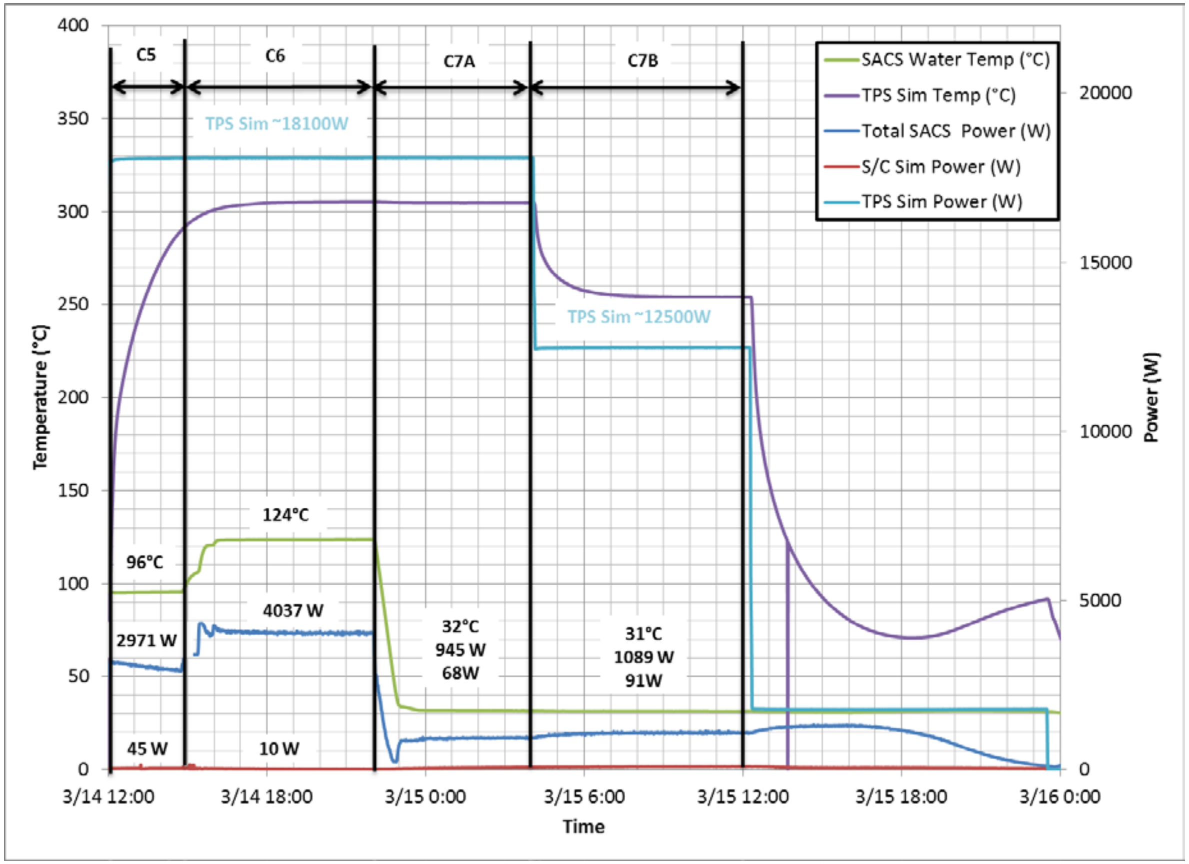
SACS Water Temp (°C)
TPS Sim Temp (°C)
Total SACS Power (W)
S/C Sim Power (W)
Temperature (°C)
Power (W)
Time
B1
1458 W
10°C, 133W
B2
19°C
1720 W
130 W
B3
39°C
2232 W
122 W
B5-1
95°C
4531 W
95 W
B6
6153 W
124°C
34 W
B5-2
98°C
4640 W
54 W
B5-3
90°C
4265 W
58 W
3/5 0:00
3/5 6:00
3/5 12:00
3/5 18:00
3/6 0:00
3/6 6:00
3/6 12:00

Back Up C-2 / B



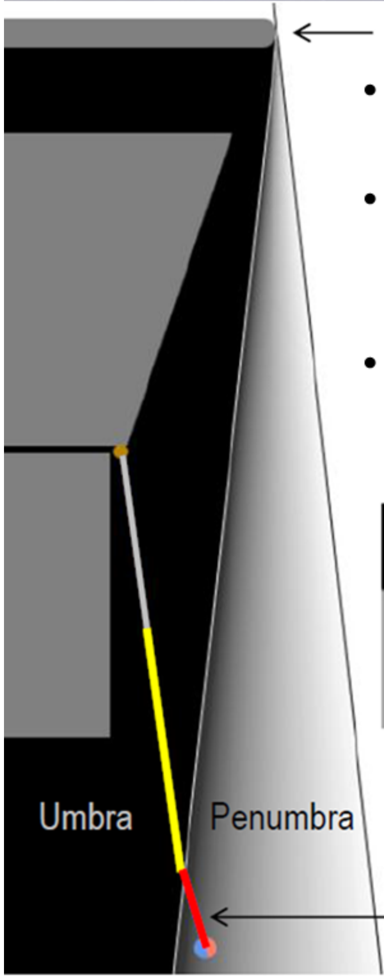
SACS Water Temp (°C)
TPS Sim Temp (°C)
Total SACS Power (W)
S/C Sim Power (W)
B1
B3
B4
B5
B6
1154 W
15°C, 116W
1620
38°C
110
2604
73°C
97
3347
94°C
80
4612 W
124.3°C
30 W
Temperature (°C)
Power (W)
Time
400
350
300
250
200
150
100
50
0
8000
7000
6000
5000
4000
3000
2000
1000
0
3/13 0:00
3/13 6:00
3/13 12:00
3/13 18:00
3/14 0:00
3/14 6:00
3/14 12:00

Back Up C-2 / C

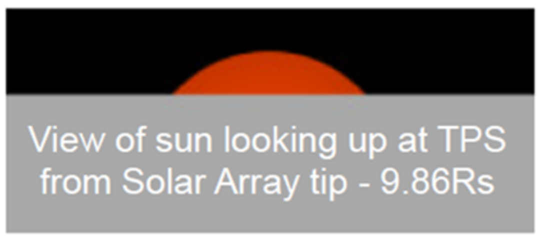


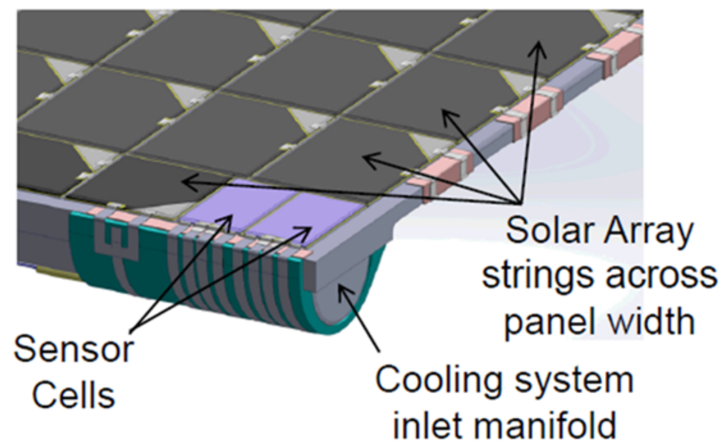
C5
C6
C7A
C7B
TPS Sim ~18100W
TPS Sim ~12500W
124°C
96°C
4037 W
2971 W
32°C
945 W
68W
31°C
1089 W
91W
45 W
10 W
SACS Water Temp (°C)
TPS Sim Temp (°C)
Total SACS Power (W)
S/C Sim Power (W)
TPS Sim Power (W)
Temperature (°C)
Power (W)
Time
400
350
300
250
200
150
100
50
0
20000
15000
10000
5000
0
3/14 12:00
3/14 18:00
3/15 0:00
3/15 6:00
3/15 12:00
3/15 18:00
3/16 0:00

BU: Treating the Sun as a $1/r^2$ point source doesn't work



- Inside of ~50 Rs the Sun cannot be accurately modeled as a uniform temperature point source
- Specialized analytical software was developed (Decker, Gaddy, Marsh) to properly account for Suns spectrum and geometry
  - especially beneficial inside of 50 Rs
- Sun model output used calculate SACS absorbed heat and predict system temperature

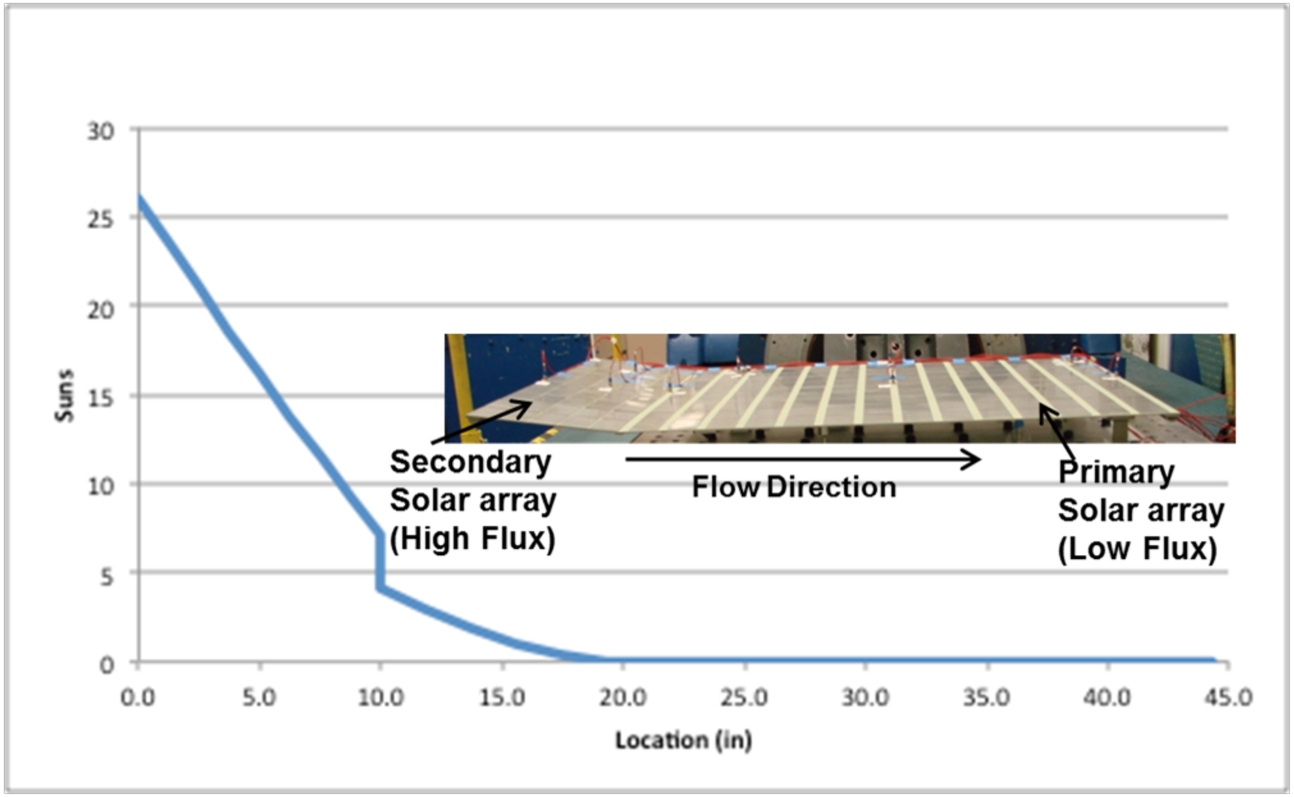




Note: Fig indicates 1 pair of sensor cells /wing corner; flight wing includes 2 pairs/wing corner

BU: 9.86 Rs Nominal Profile

Location (in)	Suns
0.0000	26.02
1.2500	23.52
2.5000	21.04
3.7500	18.58
5.0000	16.15
6.2500	13.78
7.5000	11.48
8.7500	9.27
10.0000	7.18
10.0000	4.16
11.8745	3.01
13.7490	1.96
15.6235	1.06
17.4980	0.36
19.3725	0.00
44.3149	0.00

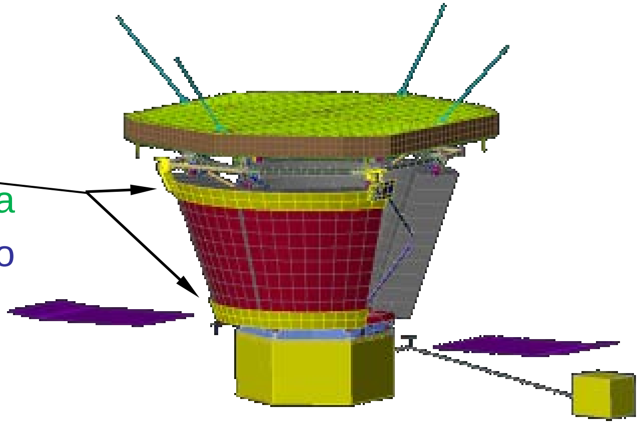


Typical of the heating profiles provided for thermal analysis

Back Up Thermal Model Summary

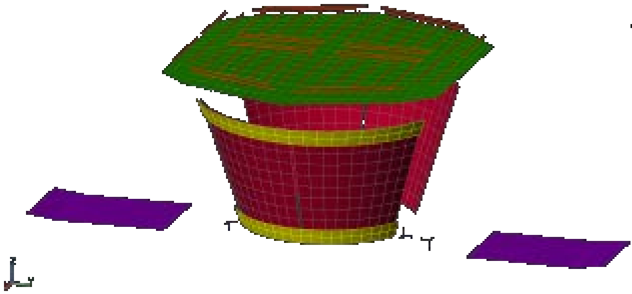
ITVT Thermal Correlation Summary

- Thermal model built for the ITVT TVAC test configurations
  - Run with (Configuration 1) and without (Configuration2) platens
  - Radiators 1,4 have 5" tall MLI blankets as shown
  - After some adjustment, model shows good correlation to test data
- Thermal model modified to represent flight-like configuration and run to generate flight predicts
  - Platens rotated toward the SC for hot cases
  - Parameters adjusted from the test model as shown in the table below (mainly for flight platens, and space boundary T)
  - Radiator blockage blankets adjusted to 6" tall



ITVT full thermal model

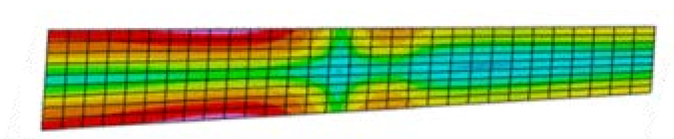
Parameter	Model	Flight	Unit
Platen area	0.73	0.776	m2
Platen front emissivity	0.758	0.71	
Platen back e*	0.03	0.03	
Platen Ae	0.553	0.551	m2
Platen width	25.6	27.2	in
Platen width	0.650	0.690	m
Radiator area, each	1	1	m2
Radiator effective front emissivity	0.8	0.8	
Radiator MLI area coverage, total	0.525	0.618	m2

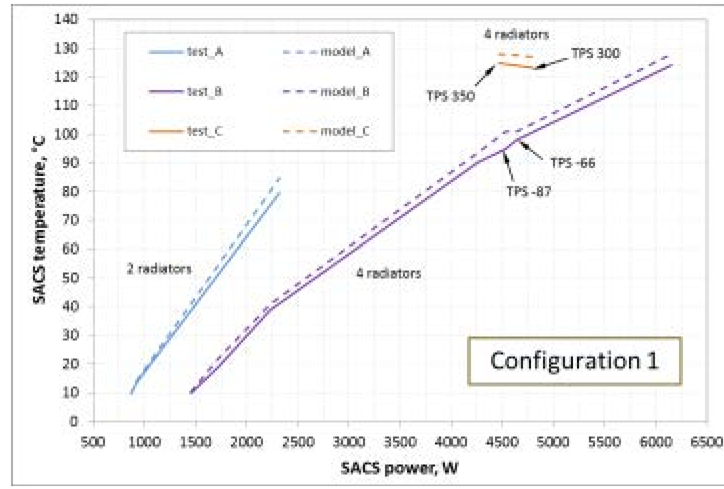


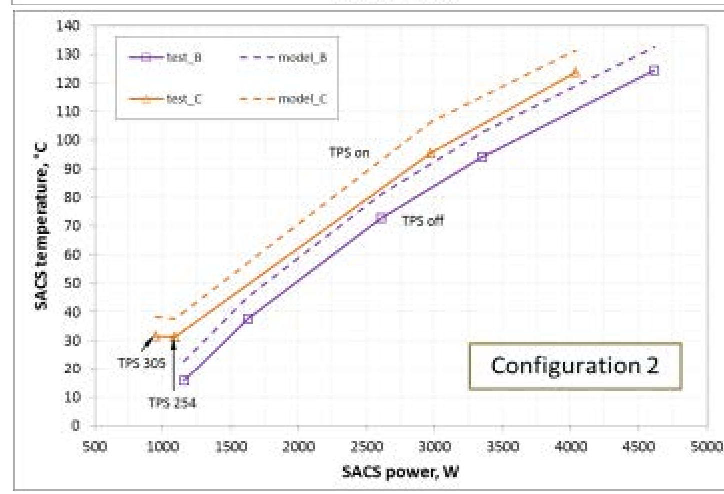
Primary SACS components

ITVT Thermal Correlation Model Adjustments

- Initial thermal model runs showed marginal agreement, but over-predicted water temperatures for the test power input over all cases
  - Configuration 1: 4 ° C
  - Configuration 2: 8 ° C
- Adjustments were made to the thermal model to better represent the test parameters
  - Increased platen thermal nodes from 1 to 22, with water node under each
  - Input power to the radiator fins adjusted to account for fin efficiency effects of adding heat to the edges of the radiator fins
    - Verified with detailed fin model, indicating loss of efficiency due to non-uniform temperature across the fin

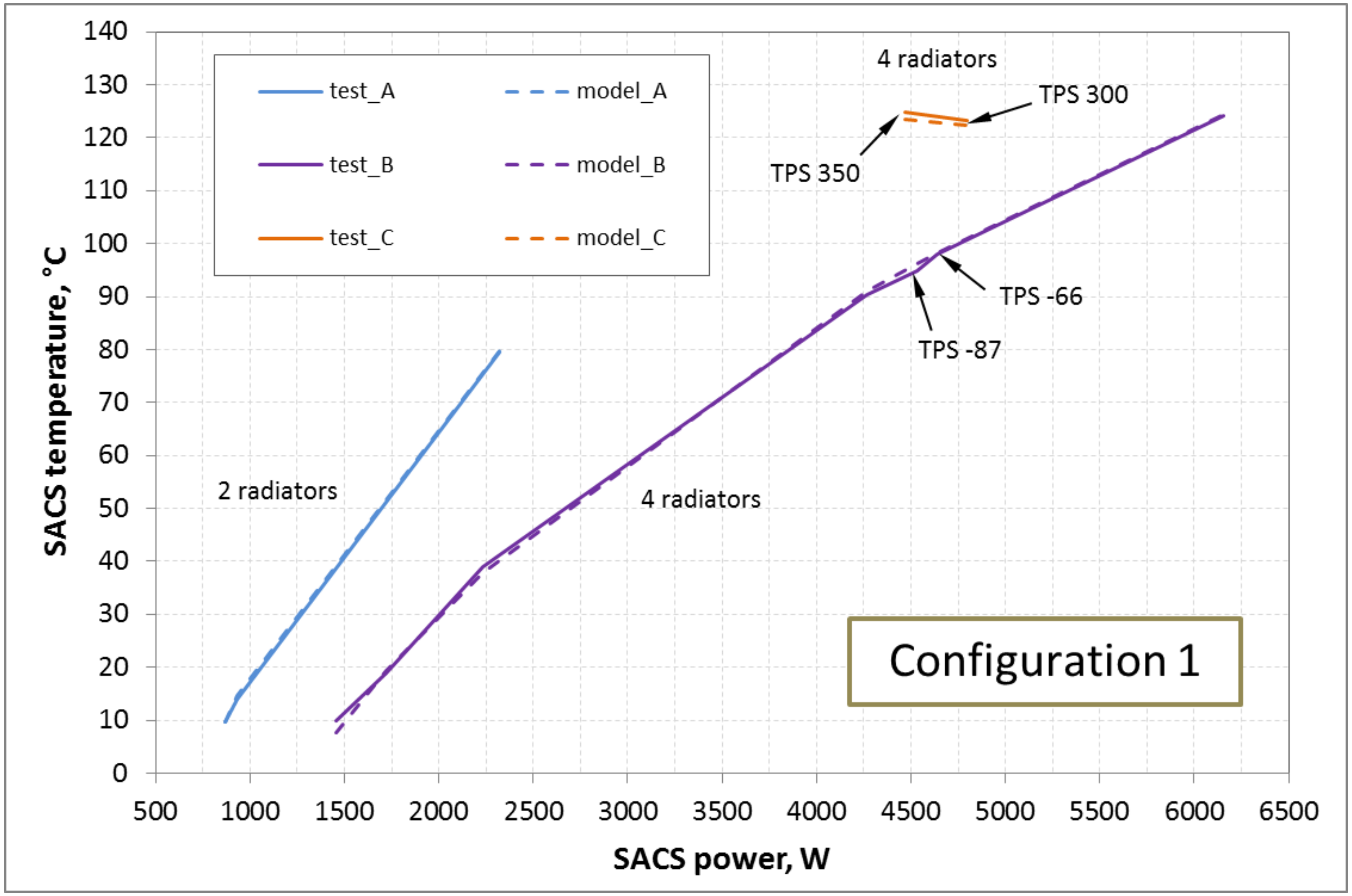






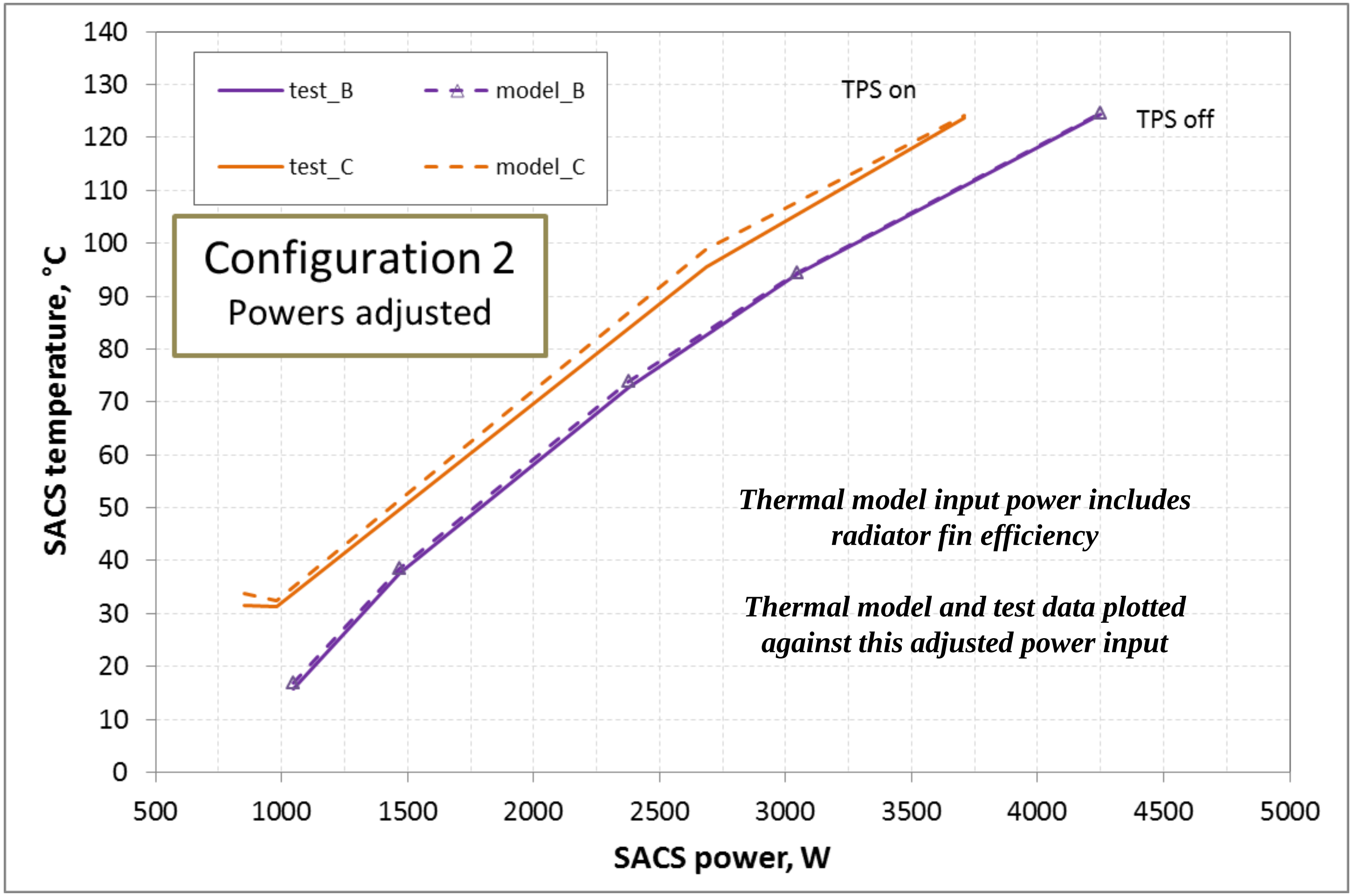
ITVT Thermal Configuration 1 Model Predicts and Test Data Comparison

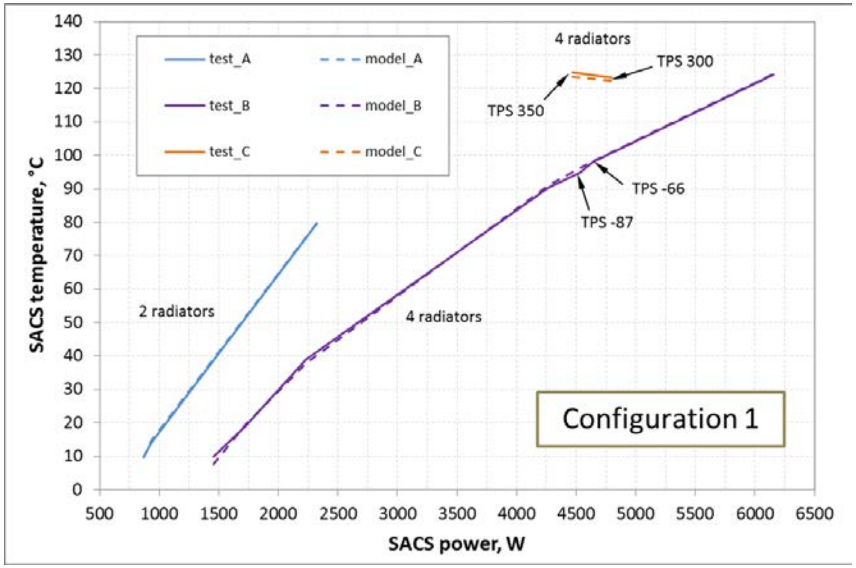
- Adjusted ITVT thermal model shows good agreement (< 1 ° C) as compared to the test data over all power levels, for 2 and 4 radiators



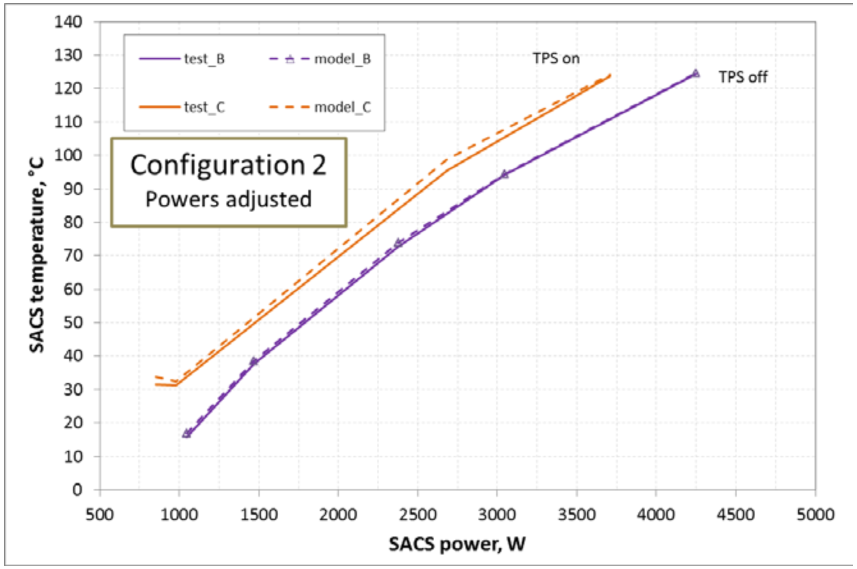
ITVT Thermal Configuration 2 Model Predicts and Test Data Comparison

- Adjusted ITVT thermal model shows good agreement (~ 1 ° C TPS off, ~ 3 ° C TPS on) as compared to the test data over all power levels





test_A
model_A
test_B
model_B
test_C
model_C
4 radiators
TPS 300
TPS 350
TPS -66
TPS -87
2 radiators
4 radiators
Configuration 1
SACS temperature, °C
SACS power, W

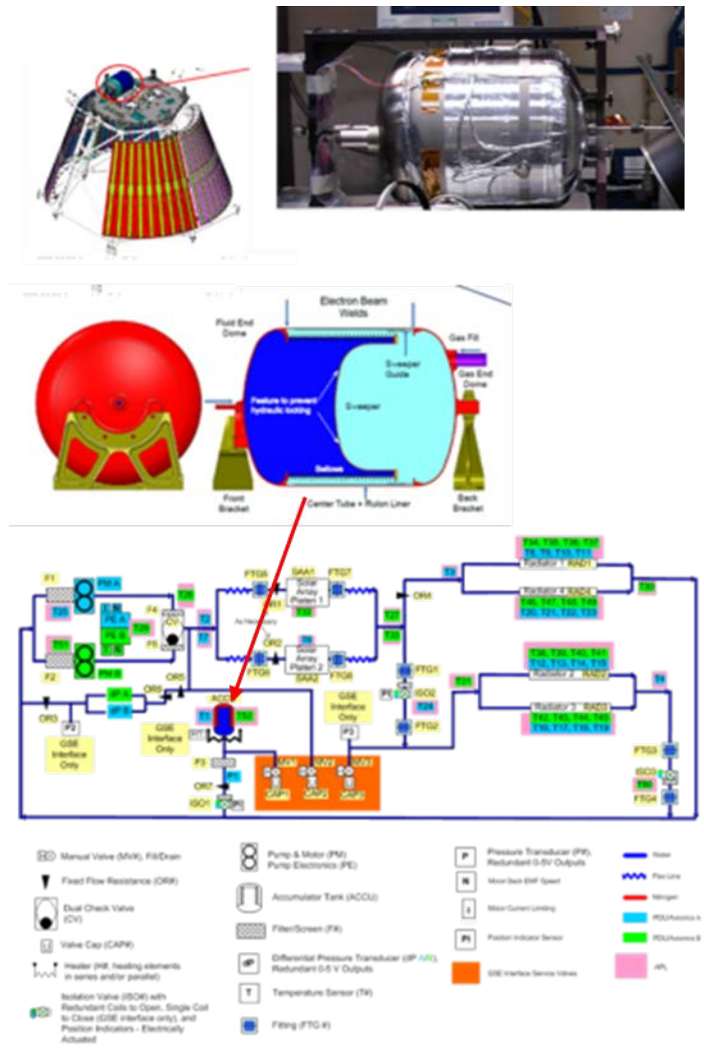


test_B
model_B
test_C
model_C
TPS on
TPS off
Configuration 2
Powers adjusted
SACS temperature, °C
SACS power, W

BU The Accumulator Failure

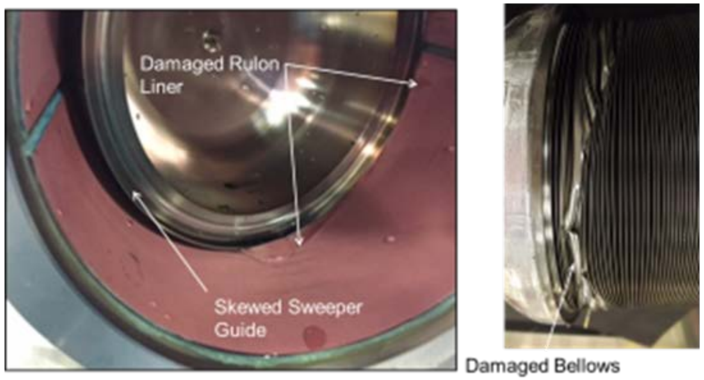
What does the Accumulator do?

- **Key Design Function**
  - **Stores the fluid required for the mission and is used for**
    - **Initial post launch system activation (SA’s + two radiators)**
    - **Final radiator activation (L+42 days)**
  - **Fixed gas charge provides system pressure to prevent cavitation at the pump**
    - **Nominal maximum system water temperature is 135°C**
  - **Compensates for fluid volume changes/thermal excursions (185 psia pre-charge / 210 C max temperature)**
- **Before launch, water in the accumulator is heated by an external heater to a temperature between 40° C to 50° C to overcome any cold spots in the radiators and tubing and assure the system does not freeze when it is initially wetted. The heater is controlled by three thermostats in series for fault tolerance and power is supplied by the Launch Vehicle**



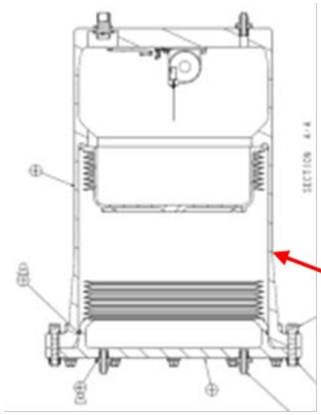
The Failure

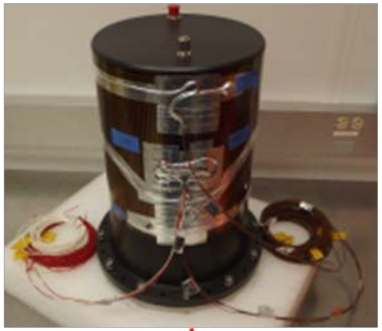
- Description: On 26 Dec 2016, the PSP flight accumulator failed the during the 2nd of 3 (planned) expulsion tests (pre-vibration) at UTAS. The failure occurred during the fill process. APL was notified immediately and an FRB was started the next day. The accumulator was scheduled to be installed into the SACS in mid-January 2017, and the completed SACS (already 7 months late) was to be delivered to APL (GSFC) the first week of February 2017. This was the last major component requiring integration before subsystem delivery
- Root Cause: Insufficient bonding to the titanium center tube shell caused blisters to form at voids in the Rulon liner that created an interference with the bellows sweeper guide leading edge while stroking causing the bellows to fail
  - Inadequate pre-forming of the Rulon created areas that were not bonded.
  - A sweeper guide with a leading edge intolerant of imperfections in the Rulon bonding also contributed to the failure
- The initial Program Impact: This was viewed as catastrophic failure and the risk to the July 2018 launch was very high. Plans were being made to absorb a slip and begin preparing for the May 21 - June 3, 2019 back-up
  - GSFC was informed and put on standby for the SACS Integrated Thermal Vacuum Test (ITVT) that was scheduled to start in late Feb 2017
    - SES shroud replacement (April 2017 and lasts 6 months) and PSP Observatory TVAC testing (December 2017) is in series with this test
  - Cost Impact to NASA would be exceptionally high
  - Mission risk increases due to the longer flight time and no viable back-up mission12

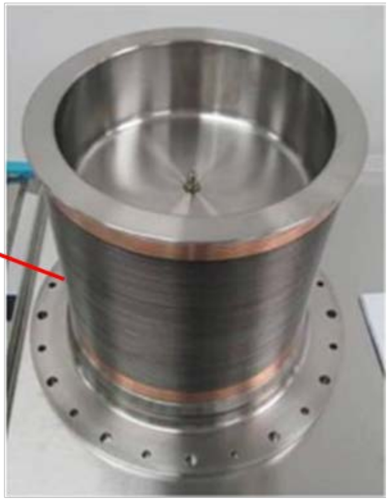


Using the Phase B Accumulator for the required SACS TVAC Testing

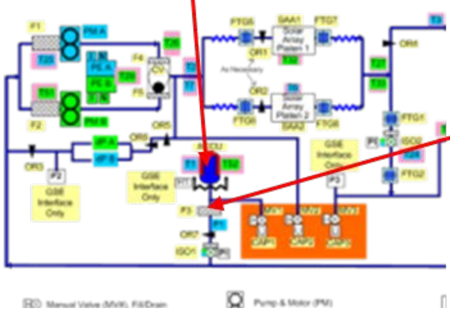
- Out of all the failures that could have happened to the SACS the accumulator allowed for the simplest recovery once decision was made to use the field joint
- During Phase B (2012-2013) a development accumulator was built to demonstrate the bellows design and this accumulator was successfully used during the SACS half system TVAC test (Oct. – Nov. 2013)
- Functionally the Phase B Accumulator (PBA) provides the same expulsion and pressure functions as the flight unit. However:
  - The PBA *thick walled aluminum* shell is cylindrical and larger and the bellows can hold ~20% more fluid (a good thing since we'll have more GSE volume)
  - PBA can only be stroked vertically
  - Cannot be physically substituted for the flight accumulator due to it's size and form factor







Phase B
Titanium Bellows
Inside of the
GSE containment vessel



Successful SACS TVAC testing

- The SACS and PBA arrived at GSFC on 21 February 2017 (~7 days later than was scheduled prior to the failure)
- The PBA was positioned external to the SACS and temperature controlled to the levels expected during the different conditions set forth by the test cases
- TVAC testing started on 2 March and concluded on 15 March. The SACS was removed from SES 290 on 20 March arrived at APL on 28 March (right on schedule)