Spitzer Space Telescope Thermal/Cryogenic System Flight Performance

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The Spitzer Space Telescope (formerly called SIRTF) was launched into an Earth-trailing, solar orbit on August 25, 2003. The Cryogenic Telescope Assembly is Spitzer's instrument payload. The design operational lifetime is 5 years, limited by the loss rate from the superfluid helium cryostat that cools the instruments to 1.3 K and the telescope to 5.5 K by vapor cooling. The thermal/cryogenic system flight performance to date is meeting expectations.

INTRODUCTION

The Spitzer Space Telescope, comprised of the Cryogenic Telescope Assembly (CTA) and the Spacecraft, is operating in an Earth-trailing, solar orbit where the influences of the Earth and Moon on the thermal system performance are negligible. This allows for a very efficient thermal system, but creating a test environment to demonstrate the expected performance was very difficult and uncertain[1].

The CTA (Figure 1) consists of four subsystems: the 360-liter superfluid helium cryostat; the multiple instrument chamber that is mounted on the helium tank; the beryllium telescope that is mounted and heat sunk to the cryostat vacuum shell; and the outer shell group[2,3]. The CTA is attached to the Spacecraft with composite supports and miniature electrical cables to control the conducted heat to the telescope and cryostat to a very low level. Shields block radiation from the warm Spacecraft bus and solar panel, which prevents sunlight on any CTA surface at all times. To reject heat the outer shell anti-sun side is coated with black paint having high emittance at low temperature. Inside the outer shell the outer vapor-cooled shield (VCS) surrounds the telescope and cryostat. Supports and electrical cables are vapor cooled between the cryostat vacuum shell and outer shell. This internal thermal system limits the heat flow to the telescope and cryostat vacuum shell to about 4 mW, which allows them to be cooled to the required 5.5 K temperature with helium vapor. This entire system can be thought of as a complex cryostat.

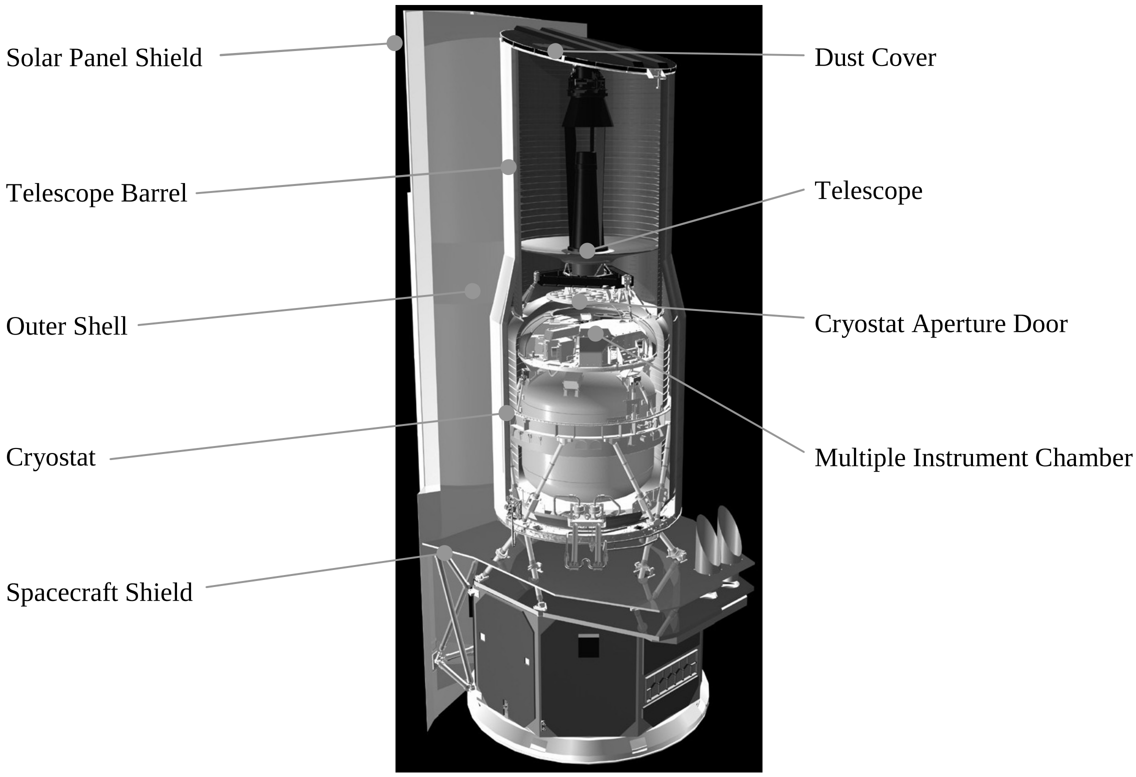

Figure 1 The Spitzer Space Telescope with cutaway view of the CTA. The Sun is always to the left.

About 5 mW heat input to the helium bath is needed to produce the flow rate required to cool the telescope and vacuum shell to 5.5 K. The instruments, which operate one at a time, dissipate between 1 and 3 mW. Parasitic heat inputs to the helium tank are negligible. Therefore, a make-up heater mounted on the tank is used to maintain a bath pressure that will produce the flow needed to cool the telescope. To maintain constant pressure the heater power level is adjusted along with changes in instrument power dissipation. The CTA helium usage rate is nearly 10 times smaller than that of previously flown, helium-cooled telescope systems.

FLIGHT OPERATIONS AND PERFORMANCE

The redundant cryostat vent valves were opened during ascent to prevent liquid breakthrough in the porous plug phase separator. Four days after launch, the telescope dust cover was ejected, and a day later the cryostat aperture door was opened. About 7 weeks after launch, the telescope focus was checked and slightly adjusted. The only CTA operation after that, not including the instruments, is use of the make-up heater to control telescope temperature as discussed below.

Cooldown performance

Figure 2 shows helium bath, porous plug external surface, and inner VCS temperatures during the first 9 days of flight. Temperature response of the inner VCS, which surrounds the helium tank, to aperture door opening can be clearly seen and was used to verify door opening. Bath temperature exceeding the lambda point (2.18 K) might allow catastrophic porous plug breakthrough[4]. Therefore, to account for uncertainty in porous plug performance in the high-flow regime, conservatively high plug impedance was used in the model. This is why the predicted peak bath temperature is higher than the actual value. Change in temperature drop across the plug, not shown in the figure, was used to verify vent valves were open.

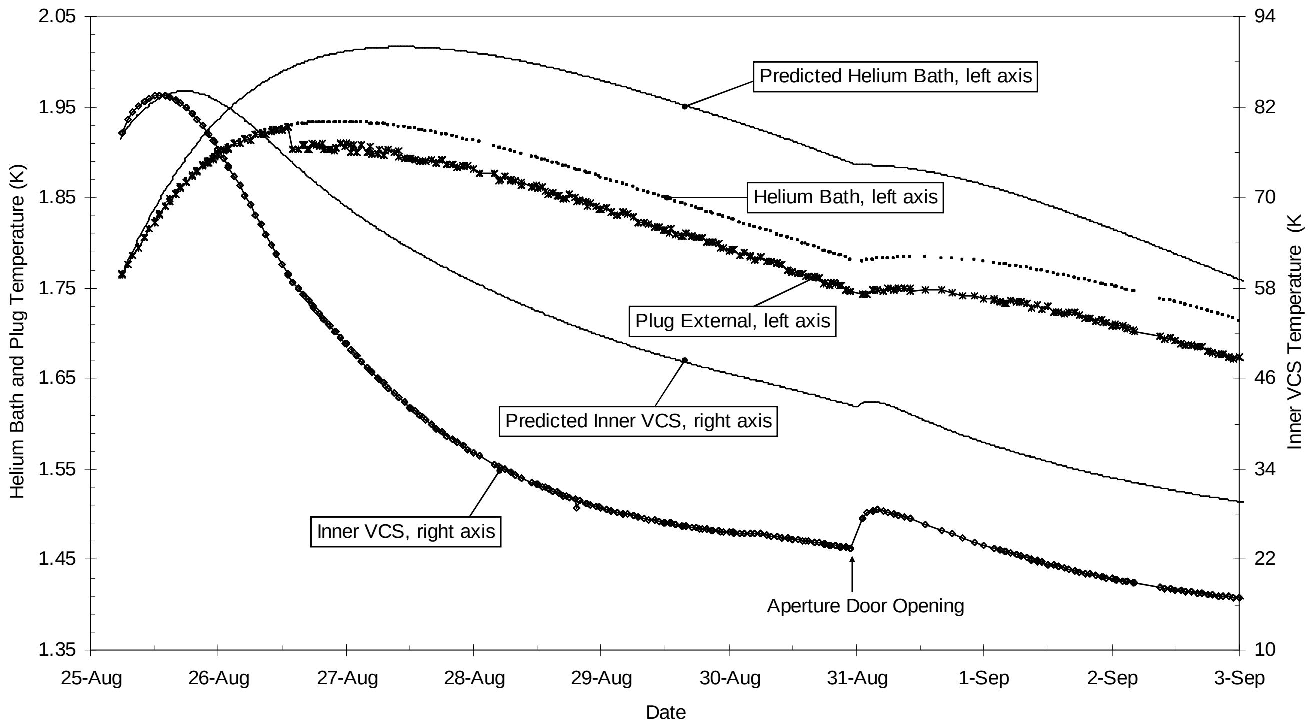

Figure 2 Critical temperatures during the early stages of cool down are shown, along with predictions.

The Spitzer CTA is a unique cryogenic telescope in that it was launched warm. The telescope cooled from 290 K to 5 K in 41 days. This warm launch architecture, made possible by the flight thermal environment, reduced the mass of the cryostat. However, the large changes in material properties over this wide temperature range created optical alignment risks and transient thermal model uncertainties. And the cooldown performance could not be realistically test verified under flight-like conditions.

Two processes drive the cooldown: radiation to space and vapor cooling using the helium effluent. Soon after launch, when the outer shell and telescope were warm, the cooling rate was dominated by radiation. Three weeks after launch, when the outer shell reached its stable temperature, vented helium vapor controlled the remaining telescope cooldown. Once in this regime, flow and telescope cooling rates were controlled with the make-up heater. The outer shell radiates 86% of its incident heat load to space at its 34 K operating temperature; the remainder is transmitted to the outer VCS. Regions between the outer shell and telescope also radiate significant levels of heat to space, but at 5.5 K the telescope does not. Raising or lowering the net power dissipation into the helium tank slowly changes the helium temperature and pressure, thus increasing or decreasing the vapor flow.

The cooldown process was modeled with an integrated thermal math model and fluid flow model using SINDA/FLUINT software from C & R Technologies. This integrated modeling approach provided predictions of helium usage, vapor cooling, and component temperatures as functions of time with instruments and make-up heater power as input. As mentioned, this model could not be strictly validated by test. However, steady-state models were test verified both at room temperature and near flight temperatures. The transient model matched the steady-state models at each end of the temperature range.

Figure 3 compares the flight cooldown data to the pre-launch model predictions. Although there are deviations, the general agreement is very good. After the dust cover was ejected, the outer VCS cooled faster than predicted, indicating the heat rejection to space was underestimated in the model. The predicted telescope and outer shell temperatures match the flight data quite well. Over the cooldown temperature range, thermal conductivities, bolted joint conductances, specific heats, and infrared emittances change substantially. For example, the specific heat of aluminum decreases by a factor of 600 going from 300 K to 10 K. There is remarkable agreement between the flight data and transient predictions considering that the model was not test verified. Note in Figure 3 the impact of dust cover ejection on telescope temperature; this response was used to verify the cover had been ejected.

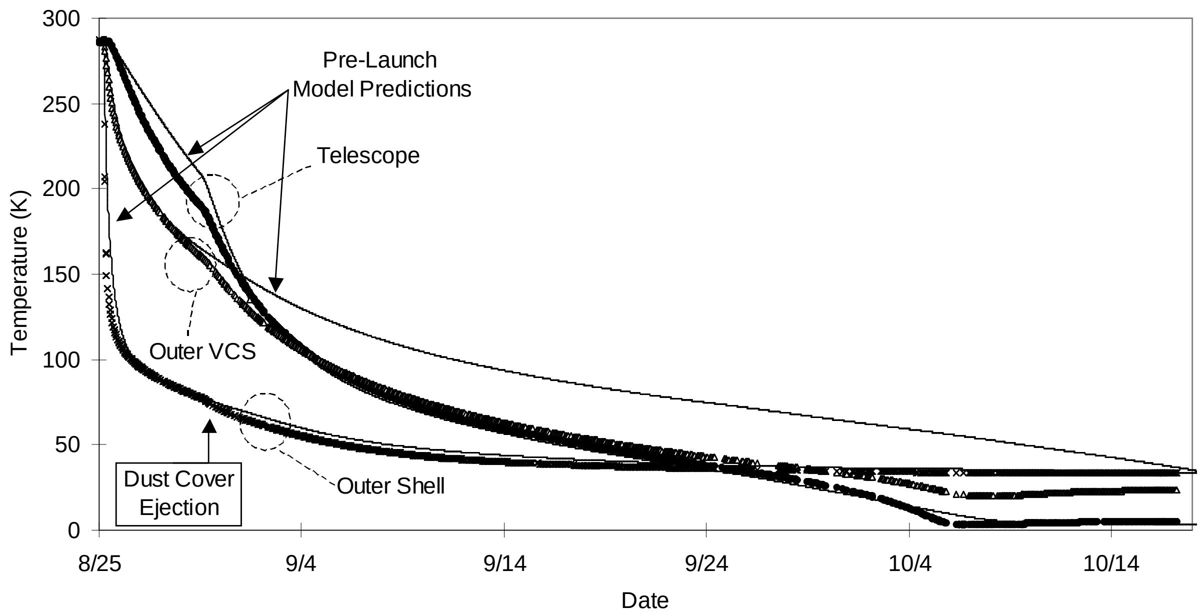

Figure 3 Cooling profiles of telescope, outer VCS, and outer shell after launch are compared with predictions. Thin lines are model predictions. Symbols are flight data. The response of the telescope temperature to dust cover ejection is evident.

Prior to launch, an aggressive schedule of instrument and subsystem flight tests was planned based on pre-launch cooldown temperature predictions using a nominal prescription for make-up heater use. Many of the instrument tests required specific telescope temperatures, and scheduled events were inter-related, leaving little flexibility. We began powering the make-up heater to accelerate cooldown 21 days into flight. The transient model did not have the accuracy to predict telescope temperatures to within a degree, as was needed at times to hold schedule. Therefore, we tracked deviations from the model and used the model to predict the sensitivity of the cooling rate to heater power. Thus, even an inexact model proved useful in making slight modifications to the heater prescription so that all temperature goals were met. Figure 4 shows the instrument temperature requirements and telescope cooldown profile as it cooled below 100 K. Make-up heater power was adjusted along with instrument power dissipation, and levels up to 10 mW were used. The telescope cooled below the 5.5 K requirement 41 days after launch.

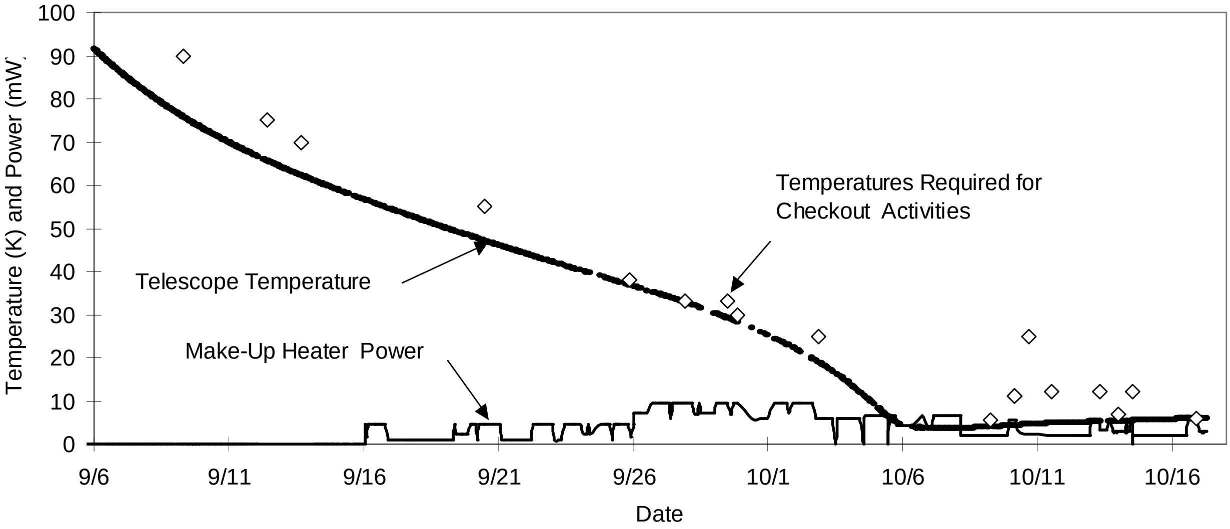

Figure 4 The telescope cooldown profile is shown along with temperatures required for scheduled instrument test activities. Also shown is the heater power used to control the telescope cooling rate to meet requirements.

Helium mass measurement, flight thermal balance test, and lifetime prediction

The cryostat includes a calorimetric helium mass gauge to provide a reliable determination of helium mass at the end of the cool down phase and then occasionally throughout the mission. The operation consists of applying 480 mW of heater power to the tank for 7.5 minutes while measuring the temperature rise. Helium mass was determined to be 43.4±1.8 kg at the end of the 2-month in-orbit checkout phase. This is a serendipitous 6 kg more than the model predicted. This is due to the conservative porous plug characteristics assumed in the model, which resulted in overpredicted flow rate during early stages of cooldown. The measured mass uncertainty comes primarily from the 5 mK absolute accuracy limitation of the temperature measurement.

We performed a thermal balance test to determine the helium flow rate required to hold the telescope at 5.5 K. This 3-day test consisted of stabilizing the telescope temperature at ~5.5 K while putting an accurately known amount of heater power into the tank. The test showed a flow rate of 22 - 28 mg/day is needed, which compares well to the pre-launch model prediction of 21 - 33 mg/day. The test uncertainty comes primarily from the uncertain knowledge of the film flow through the porous plug, which essentially results in flow that is not caused by the heat input and therefore must be estimated by analysis.

Results of the mass gauge measurement and thermal balance test indicate a mission lifetime of 4.0 - 5.3 years (if the telescope is held at 5.5 K). The specified requirement was 2.5 years minimum with a goal of 5 years. Although the helium usage rate is not quite as good as the nominal prediction, the lower-than-expected helium loss during cooldown compensated for it. It is anticipated that another helium mass measurement will be made about a year from launch, and the results will allow a more accurate determination of remaining helium lifetime.

Throughout design and ground testing, we made nominal, worst-case, and operational predictions of lifetime (Figure 5). Because an accurate ground test was not possible, we carried a large uncertainty between nominal and worst-case predictions. However, Figure 5 shows that flight performance is close to nominal predictions. The operational lifetime prediction is based on the nominal model, but with the telescope temperature allowed to float with the instrument needs.[5] Only the longest wavelength channel requires a 5.5 K telescope; most channels require no less than 20 K. This fluctuating telescope temperature operation is achieved through careful use of the make-up heater. Based on preliminary results, it is expected to reduce helium usage rate ~9%, extending the expected mission lifetime to 4.3 - 5.8 years.

Steady-state temperature data

The temperature data and pre-launch predictions are shown in Table1. The spacecraft shield, solar panel shield, and outer VCS are warmer than predicted. We believe this is due to overestimates of the heat rejection from the shields to space and/or the performance of the insulation on the warm sides of the shields. Since radiation is a small part of the heat flow from the Spacecraft bus to the CTA, the slightly warmer spacecraft shield has little effect on outer shell temperature. Since only 25% of the outer shell

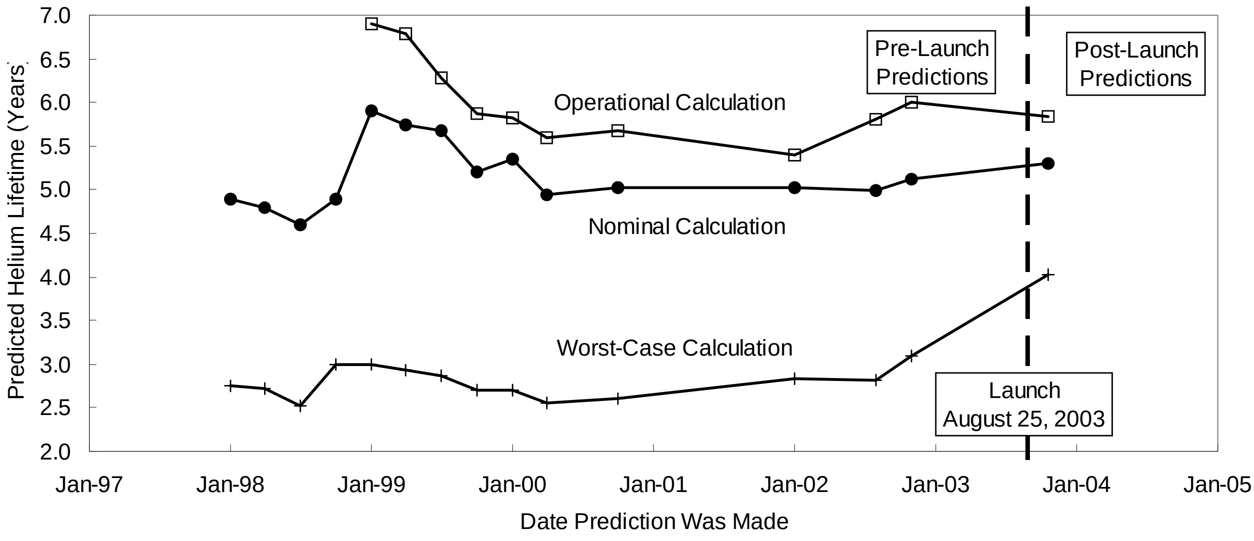

Figure 5 Helium lifetime predictions made over the last six years through design, testing, and flight.

heat load comes from the solar panel shield, the effect of the warm solar panel shield is also small. The heat load on the telescope and cryostat is directly dependent on the outer VCS temperature, explaining why the helium usage during observations is somewhat greater than the nominal prediction. Although the porous plug temperature drop is significantly less than predicted, the plug appears to be functioning properly.

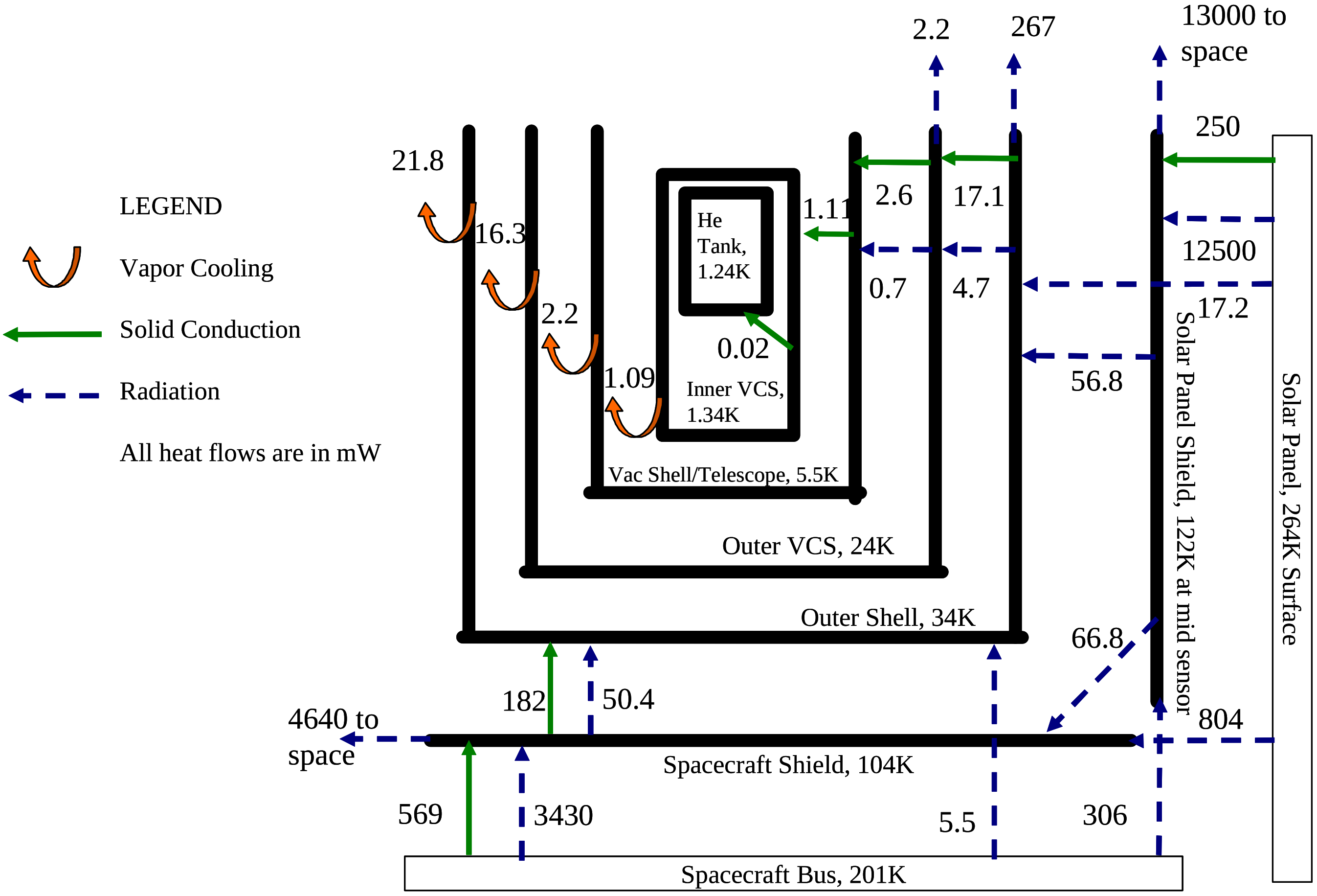

Figure 6. Predicted heat flow diagram for operational steady-state conditions. Combined instrument and make-up heater heat load is 5.3 mW to achieve 5.5 K telescope temperature.

The heat flow diagram, Figure 6, shows that radiation greatly dominates solid conduction in the warmer region of the system, and solid conduction dominates in the colder region. This is of course as expected. The diagram also shows how important vapor cooling is to achieving the telescope 5.5 K temperature.

5.3 mW heat is required to produce enough helium flow to cool the telescope; about half comes from the instrument and half from the make-up heater.

Table 1 Comparison of flight steady-state temperatures and pre-launch predictions (worst-case and nominal).

	Parameter	Value at Launch	Steady State Value	Predicted Value
Temperatures (K)	S/C Shield	285	104	99 - 110
	Solar Panel Shield	285	125	91 - 101
	Outer Shell	285	34	32 - 36
	Outer VCS	285	24	17
	Vacuum Shell & Telescope	285	5.5	5.5
	Inner VCS	79	1.3	1.3 - 1.4
	Helium Bath	1.76	1.24	1.21 - 1.26
Plug Temperature Drop (mK)		0	4	12

CONCLUSION AND ACKNOWLEDGEMENT

The Spitzer Space Telescope cryogenic/thermal system is performing close to pre-launch expectations.

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