Thermal validation of the design of the CFRP support members to be used in the spatial framework of the Herschel Space Observatory.

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FE thermal models of the support members for the low temperature components of the Herschel Space Observatory have been validated by measurements at 1.8K. The Herschel Space Observatory structure is briefly introduced. The thermal modelling of two designs of support member is discussed and the final designs presented. The design of the validation test rig is described together with details of the experimental method. Observed results are presented and discussed with reference to the thermal model. The model was found to be valid to within $1.5\cdot10^{-5}$ W/K in the lateral struts and $3.29\cdot10^{-5}$ W/K in the interface struts, at a mean temperature of 6K.

HERSCHEL PROJECT BACKGROUND

The Herschel Space Observatory is due for launch by ESA in 2007 and will capture images of the far infrared universe through three instruments:- a camera (PACS), a high resolution spectrometer (HIFI) and a photometer (SPIRE) all of which sit on an optical bench and are cooled to less than 3K. The cooling of these instruments is to be achieved by placing the optical bench inside a large cryostat which contains a superfluid helium tank at 1.6 K and uses a circulation loop to deliver the superfluid helium to the bench. The configuration of the cryostat is shown in the schematic diagram, Figure 1, where it may be seen that the optical bench and helium tank are supported from a spatial framework, consisting of two aluminium frames which straddle the helium tank.

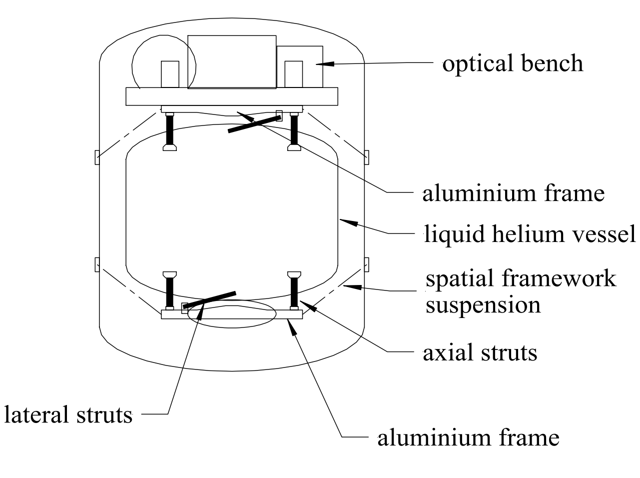

Figure 1 Schematic diagram of Herschel cryogenic assembly

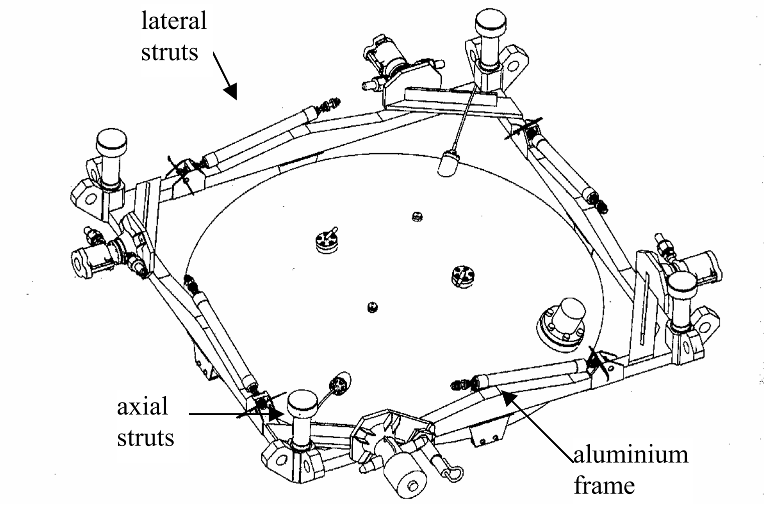

Figure 2 Lower spatial frame showing CFRP support struts

The spatial frames are illustrated in Figure 2.The helium tank and optical bench are attached to the spatial framework by a system of axial and lateral struts and the frames are supported from the wall of the cryostat by an additional assembly of struts. The cryostat wall will be at an estimated temperature of 10K.

This paper is concerned with the interface between the helium tank and the spatial framework. The interface has been designed to minimise heat transfer to the helium by using high strength low conductivity struts of reduced cross section and high aspect ratio. The strut configuration is shown in Figures 3 and 4. They are constructed from carbon fibre reinforced plastic (CFRP) tube with crimped and glued aluminium alloy end fittings.

In addition to providing support with thermal isolation the interface structure must compensate for the thermal contraction of the tank without inducing stresses on the optical bench and to this end the interface struts use coated ball and socket joints as end fittings as shown in Figure 4.

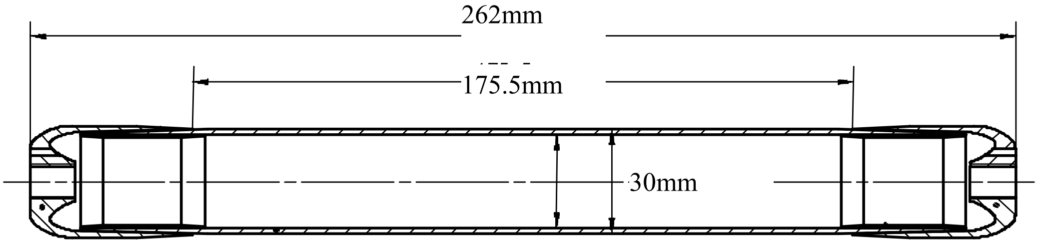

Figure 3 Lateral strut

STRUT DESIGN AND THERMAL MODELING

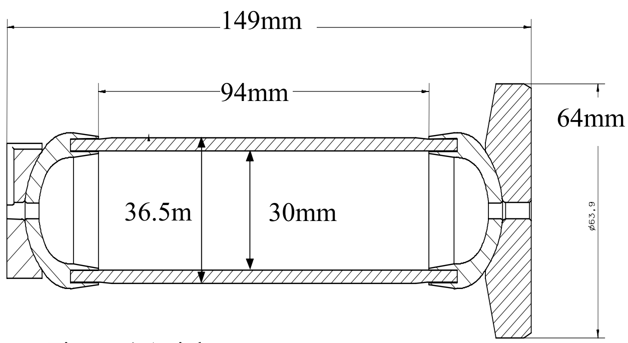

Figure 4 Axial strut

The designs of the lateral and axial struts are shown in Figures 3 and 4. A Finite Element Model (FEM) was developed to predict the thermal behaviour of the struts under varying temperature conditions and included radiation heat transfer from the cryostat wall.

Thermal modelling was done using thermal simulation software from MAYA [1] and thermo-physical property data obtained by:- [2] Radcliffe and Rosenberg, and [3] Bansemir and Haider.

Conductances calculated from the FE model for two different sets of boundary conditions are shown in Table 1. These are for:- cold end temperature: 1.6K and cryostat wall temperatures of 6K and 20K. The predicted operating conditions are for a cold end temperature of 1.6 to 1.8K and high end temperature of 10K, giving a mean temperature in the struts of approximately 6K.

Table 1 Predicted conductance data for axial and lateral struts

High end temperature - K	**Conductance – W.K^{-1}**	
	Axial struts	**Lateral struts**
6	8.4×10^{-5}	2.1×10^{-5}
20	2.7×10^{-4}	6.7×10^{-5}

VALIDATION MEASUREMENTS

Method

The method of measurement followed, to determine the thermal conductances of the struts, was to:- mount one end of selected samples of the struts on a surface cooled to 1.8K, then apply heat to the free ends, observing their rise in temperature as a function of the heat supplied. The measurements were of very low conductances, measured at low temperatures and care was taken in the design of the measurement system, to ensure that parasitic heat leaks were not significant in the measurements.

Measurements were made in a vacuum insulated cryostat, constructed as illustrated in Figure 5. Two samples of each strut design, were screwed to the base of a copper pot which could be filled with liquid helium at 4.2K and then pumped; using a rotary vane vacuum pump, to reduce the vapour pressure of the helium to 16mbar, thus obtaining a pot temperature of 1.8K. The pot was suspended in the cryostat by two stainless steel fill/vent tubes which were used for the initial filling with liquid helium and subsequent pumping. A valve in the line to the pump was used to control the pumping speed and thus the helium vapour pressure. By this arrangement it was possible to control the helium temperature to 1.8 ±0.1K

An aluminium radiation shield was placed around the pot and was cooled by the first stage of a two stage G-M cryocooler, to approximately 50K. The first stage of the cryocooler was also connected by a thermal link to the fill/vent tubes, to intercept conducted heat from ambient room temperature, which otherwise would have reached the pot. The second stage of the cryocooler was used to cool a charcoal sorption pump to approximately 10K, to maintain a high vacuum in the cryostat and around the test samples. To minimise radiant heat transfer to the test sample, a second, aluminium radiation shield was screwed to the bottom of the helium pot and surrounded the samples. Ge resistance thermometers were attached to the bottom plates of the radiation shields and the shields were wrapped with multilayer superinsulation.

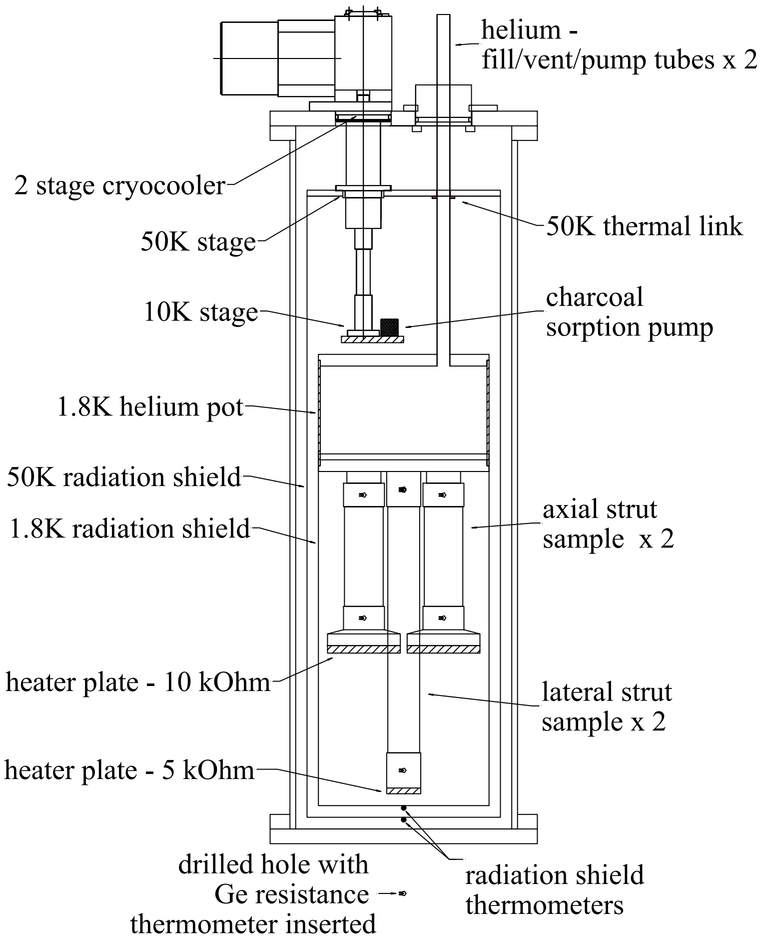

Figure 5. The test cryostat

Heaters

Heat was applied to the samples by means of electrical heater plates attached to the free ends of the struts. The heater plates used on the lateral struts were ~10mm thick aluminium disks, to which were glued 5 x 1kOhm ceramic heater chips. The heater plates on the axial struts were constructed using ~5mm thick copper flanges to which were glued 10 x 1kOhm ceramic heater chips. High heater resistances were selected so that the required operating current could be small and could be supplied using 0.127mm diameter insulated phosphor bronze wires within the cryostat, without significant I^2R heating of the wires and without significant thermal conduction through them.

The heater plates were wired in series and therefore received a common current. Their relative resistance was chosen so that the warm end temperatures of the struts would be roughly the same during the tests and there would therefore be no heat transfer between them through the connecting wires.

The voltage across each heater was measured using pairs of non-current carrying voltage taps. These were made using the phosphor bronze wire and were thermally connected to the 1.8K pot at a wire length of ~400mm from the heaters. The thermal conductance of these, based on a material (Cu + 5%Sn) conductivity of < 4W/m.K [4] was calculated to be 1.3×10^{-7}W/K and conduction through the wires, from the heater at a temperature of 20K, was conservatively estimated to be 2.4×10^{-6}W per wire. This represented <0.1% of the heater powers.

Thermometers

The aluminium ends of the struts were drilled and thermometers inserted. The thermometers used were Ge film on GaAs resistance thermometers supplied by the Institute of Semiconductor Physics, Kiev [5]. They were individually calibrated over the range 1.8 to 300K and supplied with individual interpolation polynomials and tables. Their R/T response was exponential with typical sensitivity at 1.8K of ~-6.5kΩ/K reducing to ~-23 Ω/K at 30K. The thermometers were measured using a four-terminal arrangement of independent current (500nA) and voltage wires. As for the heaters, connection was made using phosphor bronze wires thermally anchored at 1.8K and the conduction to the 1.8K pot from each thermometer, for a warm end temperature of 20K was therefore estimated to be 4x 2.4×10^{-6}W.

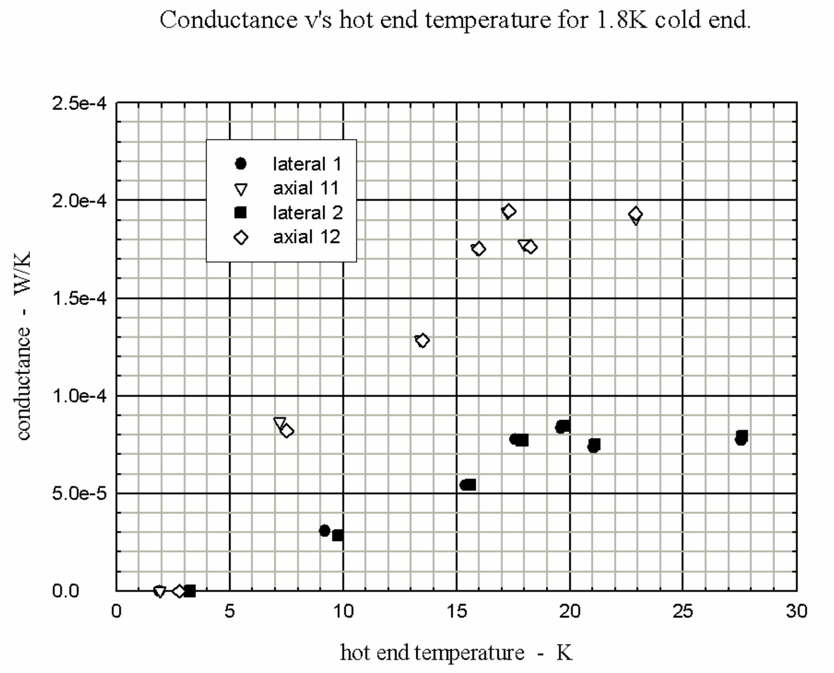

Figure 6 Measured conductance data

Data acquisition

During measurement, the thermometer resistance and heater powers, were logged at three minute intervals using an Agilent 34970A data acquisition unit. The increases in temperature of the heated ends of the samples were monitored until they reached a steady state, at which point the high and low end temperatures were recorded together with the heater power. The heater power was then increased and the measurement process repeated to produce a data table of the steady state temperatures versus heater power.

RESULTS AND CONCLUSIONS

Conductance was calculated from the heater power divided by the temperature difference observed across the samples, in units of W/K. The results are summarised in Figure 6 for varying hot end temperatures. The derived values for the expected operating condition of the struts are shown in Table 2. The model was found to be valid to within $1.5 \cdot 10^{-5}$ W/K in the lateral struts and $3.29 \cdot 10^{-5}$ W/K in the axial struts, at a mean temperature of 6K.

Table 2 Modelled and measured values of conductance for 6K mean strut temperature

Description	**Model Conductance at mean T = 6K W/K**	**Measured at W/K**
Axial Strut	$7.21 \cdot 10^{-5}$	$1.25 \cdot 10^{-4}$
Lateral Strut	$1.81 \cdot 10^{-5}$	$3.3 \cdot 10^{-5}$

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Thermal modelling was done using the TMG software package from MAYA

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