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Abstract Micro-X is a NASA funded, rocket borne X-ray imaging spectrometer that uses Transition Edge Sensors (TESs) to do high-resolution microcalorimetry. The TESs are cooled by an Adiabatic Demagnetization Refrigerator (ADR), whose salt pill functions as a heat sink for the detectors. We have made a thermal model of the cryostat with SPICE for the purposes of understanding its behavior at low temperatures. Implementing modifications based on this model has further allowed us to cool the system down to a lower temperature than had previously been accessible and to improve its low temperature hold time. These modifications include a variety of schemes for power through heat sinks and tweaking the conductance between the cold baths and the refrigerated hardware. We present an overview of the model and its constituent parameters, information about thermal modifications, and a summary of results from thermal tests of the entire system.

Keywords Sounding Rocket, Transition Edge Sensors, Thermal Modeling

1 Introduction

Micro-X is a sounding rocket experiment which acts as an X-ray imaging spectrometer [1][2]. Its detectors are Transition Edge Sensors (TESs) which provide projected 3 eV resolution in the soft X-ray band from 0.3 to 2.5 keV. Since TESs require cryogenic temperatures for their operation, it is critical that we understand and optimize the performance of its cryostat.

The Micro-X cryostat (see Fig. 1) uses an Adiabatic Demagnetization Refrigerator (ADR) for cooling. Its outer thermal shields are composed of thermally insulating G10 plastic that are cooled to 65 Kelvin and 165 K. Inside of those shields is a liquid helium tank which is pumped down to 1.6 K to serve as a cold bath for the

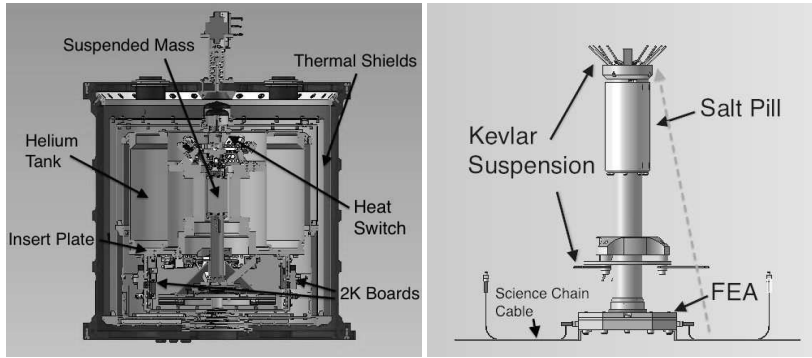


Fig. 1 Schematic of the Micro-X cryostat, with a cross section of the entire ADR (*Left*) and the suspended mass alone (*Right*). The dashed line represents the heat sinking path referred to in section 3.3. The orientation of the figure matches the orientation of the cryostat during lab testing. (Color figure online.)

system which is just outside of a magnet that provides the field for the ADR. The TES array is held in an enclosure called the Front End Assembly (FEA) along with the first two stages of SQUID readout electronics. The FEA is part of the assembly called the “Suspended Mass”, because it is held in place by a kevlar suspension. The suspended mass also contains the salt pill that provides cooling power for the ADR and is held at millikelvin temperatures during operation. The suspension is held by the “Insert Plate” which is attached to the Helium tank and also supports the “2K boards” which connect the cable bringing the science signals directly out of the FEA to the cable carrying those signals out to 300 K.

As of the fall of 2013, this design had been implemented but its performance was not up to the necessary standard, with a base temperature at the FEA of 66 mK and a hold time at 80 mK of only 1.5 hours. This didn’t give enough margin below our regulation temperature (75 mK) and the short hold time was not nearly enough to do significant calibration between cycles of the ADR. One important thing to note is that the ADR salt pill is only 75 grams, due to limits on the size of the suspended mass to prevent excess vibration [3]. Since the cooling capacity scales with mass, this inherently lowers the hold time and raises the base temperature when compared with other cryostats that can carry more massive salt pills. In order to improve its performance, we performed an array of analysis and tests, leading to the modifications described below.

2 Thermal Model

In order to better understand the behavior of the cryostat, we have constructed a detailed thermal model of the suspended mass using LT-SPICE, a software designed for modeling complex electrical circuits. Thermal heat flows follow a conductance relation which makes a simple analogy to the electrical Ohm’s law where temperature corresponds to voltage, power to current and thermal conductance to electrical conductance. Since the suspended mass is small enough to thermalize

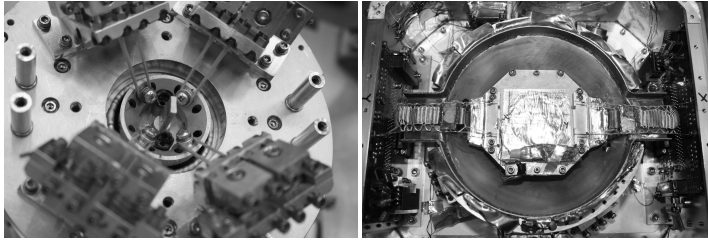


Fig. 2 The kevlar suspension and science chain cables shown here are responsible for the heat loads on the suspended mass. The kevlar suspension (*Left*) is needed for holding the suspended mass in place, and the science chain cables (*Right*) are responsible for reading out signals from the detectors. (Color figure online.)

quickly and we cool down sufficiently far in advance of making measurements, we make a steady state assumption, which allows us to model the heat bath as a simple temperature source rather than treating its heat capacity like a capacitor. This is advantageous because the heat capacity of the Ferric Ammonium Alum salt is very non-linear and would provide a significant drag on the computation speed of the model. For modeling the cooling capacity of the salt once it has been cooled down, a calculation is done separately following Ch. 9 of Pobell's *Matter and Methods at Low Temperatures* [4].

The resistive elements are modeled as temperature dependent resistors. Those resistances were found via a combination of calculations from material parameters and a series of in-lab tests. The external heat loads due to the Kevlar suspension and the science chain wire ribbon cable that connects to the FEA (Fig. 2) were modeled in two stages. Instead of simply treating them as power sources, we allowed the heat loads to vary between runs by modeling the thermal resistances of the suspension and modeling the insert plate as a temperature source.

To verify that the thermal model provided an accurate picture of what was going on inside the cryostat, we performed a series of thermal tests where the predictions of the thermal model were compared to thermometers located at key junctions while various heaters of known power were operated. By varying the positions of the thermometers and heaters between runs, as well as removing extraneous components from the cryostat that would complicate the measurement, we were able to test the majority of components in the model. Those results were then folded back in to the model, enabling it to make more accurate predictions in future tests.

3 Design Modifications

3.1 Design Considerations

Once the thermal model was complete, it enabled us to better study the causes of the high base temperature at the FEA. The primary causes were twofold, first that the base temperature of the salt which served as a cold bath for the detectors was too high and second, that the heat flowing between the detectors and the salt

was too large. The first is set by the cooling capacity of the ADR salt pill, the maximum field of the ADR magnet and the initial temperature the salt started its cooling cycle from. While the magnetic field wasn't modifiable, the initial temperature of the salt pill could be. Under the Fall 2013 design, the temperature of the suspended mass before demagnetization was 3.5 K when the helium tank had been pumped down so that its temperature was below 2 K. This was due to an insufficient thermal conductance of the heat switch between the salt and the helium bath.

The amount of heat flowing between the detectors and the salt could be lowered by reducing the total heat flowing into the suspended mass overall as well as redirecting the heat flows so a smaller percentage of it travels directly between those two components. This will then reduce the temperature difference between the salt pill and FEA, which is proportional to the power flow between them. Reducing the total heat load is also helpful for improving the hold time which is a function of the amount of power that the salt can absorb while remaining at the same temperature as well as the rate at which power is being applied onto the salt pill. The heat load can be reduced by lowering the temperature of the "warm" side of the kevlar suspension, i.e., the insert temperature.

3.2 Heat Switch Redesign

The thermal link between the suspended mass and the Helium tank prior to cool down was achieved through a heat switch. The heat switch had already undergone a series of redesigns in order to improve its basic functionality, however this redesign needed to improve its thermal conductance when closed. The heat switch had been built out of aluminum, which does not provide as good thermal conductivity as copper or gold. Therefore, the plate that connects the heat switch to the helium tank was replaced with copper and the part that contacts the salt pill bus was fitted with a copper cap, which was heat sunk onto the plate (Fig. 3). All of the contacting surfaces on these parts were then gold plated so that the Kapitza resistance across those boundaries would be minimized. These changes meant that the suspended mass could be kept at a temperature closer to the helium tank, 1.9 K instead of 3.5 K. This suggests that the conductance of the heat switch is no longer our limiting factor, and that it is now dependent on the temperature of the heat switch itself. The heat switch is mounted at the top of the Helium tank (Fig. 1) which experiences a thermal gradient such that the top is warmer once the Helium bath is pumped on so that the liquid doesn't reach the top of the tank. Improving our heat sinking between the top and the bottom of the tank should allow us to reach 1.5 K, the temperature at the bottom.

3.3 Heat Sink Design and Installation

In order to reduce the amount of heat that was passing directly between the detectors and the salt, a heat sinking strap was devised to reroute the power coming down the science chain cables away from the FEA (Fig. 1). The thermal model showed that the entirety of the heat coming from the science chain wires (2.32

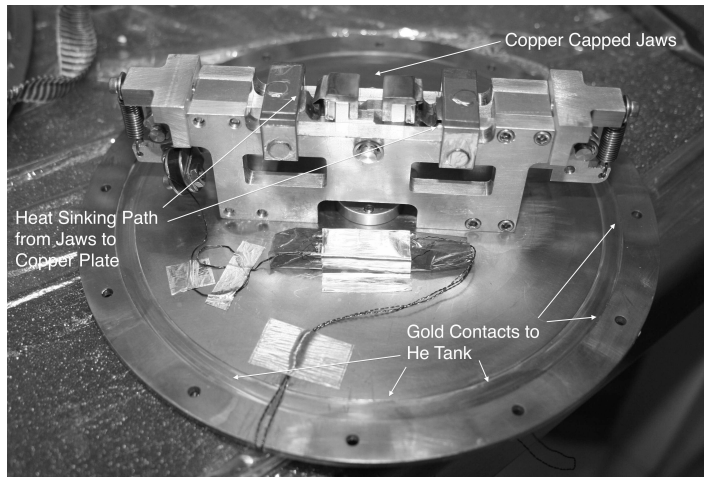


Fig. 3 The current set up for the heat switch is shown here, with the modifications made to improve its thermal conductivity highlighted for emphasis. (Color figure online.)

μW of the entire $3.59 \mu\text{W}$) ran between detector and the salt pill, causing a large temperature gap. In order to remedy this two fixes were made. The simpler one was to add a disk of stainless steel at the interface of the FEA with the supporting structure to thermally isolate it from the suspension. The other was to add a heat sinking strap that carried power away from the science chain cables to the forward bus of the salt pill (Fig. 1). Only a small remainder ($0.98 \mu\text{W}$) was left over to flow between the detectors and the aft bus. Since the two buses of the salt are thermally independent, this allowed the aft bus to experience little heat and provide a lower temperature differential between the salt and the detectors.

The heat sink was primarily composed of annealed, high purity copper with gold plated contact surfaces to maximize its thermal conductivity. In order to improve mechanical stability, most of its length is taped down to the outside shell of the salt pill since its stainless steel shell is resistive enough to prohibit any power from flowing to the aft bus through that contacting surface. The connection between the heat sinking strap and the science chain cable is located inside the magnetic shield, so it connected to the rest of the path outside as a wire, passed through a small hole in the magnetic shield proximate to the source of the wire. Since any contact between the wire and the 2 K magnetic shield would have been disastrous, a stiff Magnesium bar was positioned just by the opening in the magnetic shield to hold the wire steady and carry the heat to the next part of the copper strap.

Since the copper components of the heat strap are highly conductive, the limiting factor in the performance of the heat sink is the epoxy attaching it to the science chain wire. At the relevant temperatures, the most conductive epoxy is Stycast 1266, which posed a challenge in fabrication due to its extremely low viscosity. After making a series of test joints on mock cables, the solution was to form a folder of copper around the ribbon sealed with a layering of higher vis-

cosity epoxies (Armstrong A-1 and Stycast 2850) to form a thin cup between the ribbon and the copper strap. This was then filled with the Stycast 1266 which, having nowhere to flow to, cured in place to form a conductive bond between the two pieces. Upon installation, it was clear that there was an immediate improvement in the base temperature, allowing it to be cooled well below the 45 mK calibration limit of the GRT thermometer on the FEA.

3.4 Science Chain Redesign

In order to lower the temperature of the insert, our goal is again to increase the conductance and to decrease the power between the insert and the Helium bath. To decrease the power, the Science Chain Cable that passes from 300 K to the insert was to improve the heat sinking at 65 K to reduce the power that it dumps on the insert. The other change was to replace the wires between the 300K stage and the Helium bath for signals where fast response is not needed with higher resistance wires so that less heat would flow down those lines. We have calculated our new heat load to be 10 mW, compared to the 35 mW we had estimated it to be before.

3.5 Gold Plating

To follow the other avenue towards lowering the insert temperature, the conductance between 2K stages was increased by gold plating. Kapitza resistance between aluminum pieces limited how well heat could flow between from the relevant components to the Helium tank. In order to improve on that, the bottom of the Helium tank, the entire insert plate, and the boards that connect cabling to the insert were all plated in gold because it doesn't form an oxide layer which means that it will be significantly more thermally conductive. After gold plating, the temperature of the 2K boards dropped from 2.1 K to 1.9 K, which provides a colder warm end for the science chain cables into the suspended mass.

4 Conclusions

The hold time with these modifications is 6.5 hours, much more than the 15 minutes for flight, even after accounting for a generous estimate of vibrational heating from the vibe test [3]. This also meets an acceptable standard for laboratory calibrations, limiting the number of necessary ADR cycles during each days testing and additional improvement is expected upon the arrival of the new Science Chain Cables.

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