A four-stage continuous ADR for space missions

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Abstract The cryogenics group at NASA-Goddard has provided adiabatic demagnetization refrigerators (ADRs) for cooling detectors to sub-Kelvin temperatures in space. These ADRs were single-shot devices that produced cooling at 0.05 K for tens of hours before needing to be recycled. Our group also developed a four-stage laboratory ADR system which holds one stage continuously at 0.05 K, or colder, while using the other stages to pump heat from the continuous stage up to a heat sink near 4 K. This continuous ADR (CADR) provides a useful cooling power that is more than 10 times greater at 0.050 K than what was required by the single-shot space systems. Over the past several years, this system was updated so that it can withstand the rigors of a launch into space. We describe this development process and report its final results.

Keywords: adiabatic demagnetization refrigerator, space flight, ADR

INTRODUCTION

Future astronomical instruments will require cooling to sub-Kelvin temperatures to obtain high sensitivity. Newer generations of detector arrays need several μW of cooling at temperatures of 50 mK or lower. Sub-Kelvin temperatures in space are produced by a combination of mechanical cryocoolers at the upper temperature end and specialized sub-Kelvin coolers at the cold end. An adiabatic demagnetization refrigerator (ADR), having a thermodynamic efficiency close to Carnot, is the most efficient way to produce sub-Kelvin temperatures. It provides cyclic cooling by first raising the magnetic field in a paramagnetic material, removing the resulting heat from the material through a closed thermal switch, then isolating it by opening the switch, and cooling it by reducing the field. Our team, at NASA's Goddard Space Flight Center (GSFC), invented a method to produce high-heat-lift continuous cooling with a multi-stage continuous ADR (CADR)[1]. We demonstrated a four-stage laboratory CADR with continuous cooling of 6.5 μW at 50 mK and 31 μW at 100 mK, rejecting heat to a cryocooler at temperatures as high as 4.5 K. In later years, two new versions of the lab CADR were built using very similar components but with slightly different physical packaging of the stages. One of these, like the original CADR, was for lab use, while the other was used on a NASA balloon mission.

In 2016 we proposed to analyze and build an upgraded version of this lab CADR designed to survive the mechanical loads of a launch into space. We also proposed to add stages to reject the heat to a 10 K sink and to include an overall magnetic shield which would limit nearby stray magnetic field fluctuations to less than 5 μT. We were fortunate to receive NASA support for this effort, and in early 2017 the work began[2]. Since that time it has continued, although some elements of the original design were shelved due to limited resources. In the end, this effort focused on a four-stage CADR cooling to 0.05K and below, with heat rejection to a 4 K sink. Our goal was to modify the lab CADR design as needed for space flight, while maintaining its cooling capability. We describe this system's development and report on its test results.

THE 4 K – TO – 10 K SUBSYSTEM

Our originally proposed overall CADR system is shown schematically in Figure 1. Stages 1 – 4, on the right side of the figure, constitute a designed-for-space-flight version of the laboratory CADR. Heat dissipated by detectors is conducted to stage 1, held continuously at a typical temperature 0.05 K. Stages 2 – 4 pump the heat to a platform held continuously at approximately 4 K. Stages 5A and 5B work in parallel, cooling the 4 K platform and rejecting heat to a 10 K sink. These warmer stages form a subsystem which can be operated and tested separately from the colder 0.05 K – to – 4 K CADR. The coldest three salt pills contain chrome potassium alum (CPA), while the warmer ones use gadolinium gallium garnet (GGG). The superconducting heat switch between stages 1 and 2 is a small lead rod surrounded by a Helmholtz coil. In zero applied magnetic field at its operating temperature, the lead is superconducting and has an extremely low thermal conductance. When driven normal by a magnetic field applied by the coil, its conductance rises by several orders of magnitude, "closing" the switch. All other heat switches in the system are gas gap devices, having high conductance when filled with ^{3}He gas and low conductance when evacuated[3].

The 4 K solenoid magnets used on the coldest four stages were fabricated in our lab using commercial NbTi wire. Those of stages 5A and 5B were special 10 K Nb_3Sn

magnets developed and provided by Superconducing Systems, Inc. (SSI)[4]. We started with one such magnet, which had seen extensive use in use in our lab since 2010, and contracted with SSI to provide two additional units. Each CADR magnet is surrounded by a ferromagnetic shield to reduce stray magnetic field fluctuations, and an overall ferromagnetic shield surrounds the entire system.

During the first 18 months of this effort, the team built and tested a single-stage 4 K - to - 10 K ADR, gaining a more complete understanding of subtle geometry effects in the calculation of cooling power from a cylindrical salt pill. We also performance-tested an existing lab 0.05 K – to – 4 K CADR built with many components identical to those planned for use in our overall CADR. This work led to the discovery of occasional anomalous heating in the colder salt pills, which correlated with vibrations due to an aging lab mechanical cryocooler. Suspecting that this was due to stretching and rubbing in the Kevlar suspension legs, we initiated a study of this effect, which we eventually completed in mid 2019[5].

In late 2019, we completed assembly of the two-stage 4 K - to - 10 K CADR (shown in Figure 2) and began the first test of this subsystem. We were able to demonstrate cooling of our 4 K stage, and we spent some time adjusting our automated control software which ramped the magnet currents up and down, and opened and closed the active heat switches. During this test period, our original 10 K magnet quenched unexpectedly, and it subsequently generated an abnormally large amount of heat while its current was ramped up or down. We removed the magnet, performed numerous tests to try to understand this phenomenon, and consulted with SSI. Their conclusion was that the outer coil had sustained some subtle damage and would eventually need to be replaced. Further testing on this subsystem was postponed until the they could provide a replacement magnet. Unfortunately, it arrived in 2020 while we were forced to work remotely due to the pandemic. When we returned to lab work in 2021, limited remaining resources forced us to shelve the 4 K - to - 10 K subsystem indefinitely.

DESIGNING AND BUILDING THE 4 K – TO – 10 K SUBSYSTEM

In parallel with our work on the warmer CADR, we fabricated and assembled elements of the colder subsystem that didn't need to be re-designed. However, the salt pill suspensions for stages 1 – 3 were considered fragile, and their design was delayed until we could perform a thorough structural analysis.

In the original lab CADR, the salt pill assembly of stage 2 was suspended by six short Kevlar strings running outward at angles from the pill to connection points on the surrounding 4 K magnet mandrel. The Kevlar was looped through and epoxied inside the hole in a vented screw on the magnet end, and a short vented threaded rod at the pill end. A metal pin in the outer end loop served as a failsafe device in case the epoxy de-bonded from the inside of the hole. A leg was tensioned by tightening a nut on threaded rod end, which compressed a stack of Belleville washers under the vented screw's head. Stage 3 was identical to stage 2. Stage 1 had a similar suspension scheme, except that its small magnet and shield were part of the supported mass, suspended inside a metal frame. Also, each stage 1 leg had its threaded rod/nut end attached to the 4 K frame, with Belleville washers on the cold side. For all three stages, the free Kevlar length in each suspension leg was approximately 2 cm.

Our detailed structural analysis of the 0.05 K – to – 4 K subsystem, completed in early 2020, indicated that the Kevlar suspension strings would need to be tensioned to forces three times higher than those in the lab system. This necessitated thickening these strings, and the resulting increase in heat conduction to the coldest two CADR stages was undesirable. This led to a significant re-design of stages 1, 2, and 3 relative to the lab system. Figure 3 shows a cross section of the new design of stage 2 (or 3). Each Kevlar string now extends out through an angled support tube mounted on the shield (or the support frame in stage 1). At the outer end of each tube a stainless steel bellows, functioning as a spring, facilitates the application of the appropriate tension. The specific bellows model was chosen because it provides a similar stiffness to the original Belleville washer stack, but with much more repeatability. We actually calibrated each individual bellows, measuring its stiffness with a precision of about +/- 3%,

Figure 4A shows details of the Kevlar end bearing on the salt pill assembly. There are two nuts on the threaded rod. The one bearing on the salt pill assembly structure is tightened to set the Kevlar tension. The second one is a jam nut which prevents loosening during vibration. Figure 4B shows the outer end of a leg, where a piston-like part (shown in orange) bears on the compression bellows. The tension can be determined at any time by measuring the axial distance from the outer surface of this part to the outer edge of the support tube (shown in blue). We designed a fixture to assist in measuring this distance precisely with a depth micrometer. Our ability to set and re-measure the Kevlar tension more precisely is a significant improvement over the original Belleville washer design.

Structural analysis showed this "chicken wing" design to be acceptable, and the resulting Kevlar lengths keep the heat conduction similar to that in the lab system. The thick Kevlar strings should be strong enough to take the loads seen in a vibration test or space launch, but we performed many pull tests to confirm that the epoxy joints would also survive. We found that they could initially tolerate sufficient loads, but the epoxy occasionally de-bonded from the inside of the hole in an end piece after 8 or more thermal cycles between room temperature and 4 K. The outer pins should keep this from resulting in a total failure of the suspension system, but it is possible that some loosening of a leg may result after cycling. Assuming that this happens early enough in the test campaign, the leg tensions could be re-set to their optimum values before launch.

Stage 4 is designed differently in both our system and the lab CADR, with the salt pill suspended inside a sealed volume formed by the magnet mandrel's inner surface and two closeout structures at its ends. We also re-designed this stage, replacing a Kevlar suspension element with a wire-EDM-machined stainless steel "wheel-and-hub" part. This was done both for structural considerations and to simplify the stage's assembly process. Finally, we thickened the magnetic shields surrounding stages 2, 3, and 4 to prevent them from saturating at the highest fields, as had been observed in the laboratory CADR.

The salt pill assemblies, magnets, and superconducting heat switch were built almost identically to those used earlier in lab CADRs. For programmatic reasons our gas-gap heat switches used stainless steel in their shells instead of the titanium 15-3-3-3 which was use in earlier CADRs[6]. Although the somewhat inconvenient locations of our four stages had been driven by the inclusion of stages 5A and 5B in the original design, we kept them to avoid additional re-design work. Figure 5 is a photo of the finished CADR ready for performance testing. The stages are bolted to a platform which serves as the 4 K interface. This platform is supported above the cryostat's 3.1 K plate by thick copper posts, which are hidden in the photo. Also hidden are the two gas-gap heat switches between stages 2, 3, and 4, which hang below the 4 K platform. These switches are surrounded by a sheet-copper box, which bolts to the plate's underside and shields them from stray thermal radiation. Similarly, a drum-shaped thermal shield bolts to the top of the plate and protects the components seen in the figure. In March, 2022, after more than five years of development, the CADR was ready for operation.

OPTIMIZING AND TESTING 4 K – TO – 10 K CADR

Before the CADR performed close to its target specifications, we carried out many optimization steps. These may be divided into two categories: those which were expected as part of the complicated system's tuning process, and those which were necessary to fix hardware problems resulting from the design, fabrication or assembly of the components. The former category included training the magnets. Every time the system was cooled from room temperature to 4 K, the magnets for stages 3 and 4 had to have their currents ramped up until they quenched multiple times, each time at a slightly higher maximum current. Stage 3 was able to operate at desired currents after a couple of quenches, but stage 4 usually required a full day of training to reach its necessary maximum current of 3.2 Amps. With training completed, the CADR was ready to operate as a cooling system.

The first few test runs were devoted to tuning the three passive gas-gap heat switches between stages 2 and 3, between stages 3 and 4, and between stage 4 and the 4 K platform. Being passive switches, they were each filled with a precise pressure of ^{3}He gas and sealed before integration into the CADR. Each switch's internal charcoal getter would adsorb all of the gas and open the switch when the switch's cold end reached a specific temperature. Since the getter's precise effective area was not known, the appropriate gas fill pressure had to be determined by an "educated trial-and-error" process. This required several different test runs, each preceded by the removal, bakeout, filling/sealing, and re-installation of a switch. At best this took a full week per cycle, so the switch tuning process took months.

Once it was completed, the CADR could actually cool to useful temperatures, and we began the process of varying the individual stage maximum and minimum temperature settings to optimize its performance. This performance is defined by how much "useable" power can be applied to the continuous stage 1 with an electric heater while it maintains its desired operating temperature. When working well, the system goes through a complete cycle in approximately 30 minutes. It turns out that if each stage's minimum current during a cycle remains constant over many cycles, the system is considered stable and is successfully absorbing the heat applied to stage 1. If the stage 1 heater power is increased (keeping all other settings constant), some of these minimum current values will decrease on each subsequent cycle until they either stabilize at lower values, or they all reach zero and stage 1 begins warming. The latter case indicates that the system failed to absorb the applied heat, and we would then usually attempt to change some stage temperature settings to improve the performance. However, after any change, several hours were typically needed to see if performance improved, degraded, or stayed the same. After several weeks of this testing, we were fairly certain that the system could only be improved by making hardware changes, which fell into the second category of optimization.

The first hardware modification was to install a charcoal getter volume, along with a heater and thermometer, onto the gas fill tube of stage 4. This made the connection between stage 4 and the 4 K platform an active switch. For testing purposes, this enabled us to change the control temperature of the 4 K platform as needed, since we could manually cycle the switch independent of the stage 4 temperature. This configuration makes more sense for a future flight system, in which the exact sink temperature may vary due to cryocooler degradation over the mission life.

The next change was driven by a surprising discovery made during the testing. We noticed indications of poor thermal connection between stages 1 and 2 when the superconducting heat switch was closed. Assuming that the switch had somehow degraded, we removed it and replaced the lead conductor, taking great care to optimize the melting process that bonded it to the two copper end pieces. After re-installing the switch, we saw no change in the CADR performance. The only other conductive elements between stages 1 and 2 were an annealed copper strap, two bolted joints across gold-plated copper surface interfaces, and a solid copper structural element on the top of the stage 1 salt pill. We added four thermometers in this region to measure the temperature drop across each of these elements. Our next test run showed that the dominant thermal resistance was in the stage 1 copper piece. We removed it and measured its residual resistance ratio (RRR), which was about 3.5. This was much less than the typical 50 to 100 range expected from the grade of copper specified in the part drawing, and it explained the part's poor thermal conductance. Similar salt pill copper parts from stages 2 and 3 were found to have extremely low RRR values, so we quickly had replacement parts made. These had RRR values of about 65, so we installed them and resumed testing. As expected, we saw a significant improvement in the CADR performance.

With the system now able to pump heat at a fast rate, we found that the performance bottleneck was the ability to pass this heat from stage 4 to the cryostat's mechanical crycooler. This was a limitation of the test facility, rather than the CADR, but it kept us from demonstrating the full cooling capacity. The original conductive path from stage 4 was into the 4 K platform, down through its copper support posts into the cryostat cold plate. The center of this plate was connected via thick copper straps to the actual cryocooler cold head. Unfortunately, this plate was made using the alloy aluminum 6061, so its thermal conductance was relatively poor. Each time stage 4 was ramped to its magnetic field and its active heat switch was closed, the 4 K platform temperature would rise above 4 K. With the heat capacity of three large magnet shields attached to this platform, it cooled relatively slowly back to 4K as its heat was conducted through the aluminum alloy. This time delay ultimately lengthened the CADR cycle, limiting its cooling power capacity. We quickly mitigated this situation by adding flexible copper straps between the 4 K platform and the center of the aluminum plate near the cryocooler attachment location. This change boosted the performance significantly, and it indicated that additional straps would lead to further improvement.

CADR TEST RESULTS

The most important test result was the useable cooling power into stage 1 at 0.05 K. After much tuning of the system we demonstrated 5.4 μW, which was tantalizingly close to the original target of 6 μW. We also found that the system could lift 12 μW at 0.075 K and 25 μW at 0.1 K. Finally, we determined that 0.040 K was the coldest temperature at which stage 1 could be continuously controlled with zero added power. This result was a bit surprising, as we had expected to achieve zero-load cooling at lower temperatures. At the time of this publication we suspect that improved strapping to the mechanical cryocooler would allow us to demonstrate higher cooling powers at all of these temperatures.

We measured other relevant parameters using a careful technique to determine the total power absorbed by stage 1. When controlled at a fixed temperature, the salt pill absorbs the same total amount of energy whenever its magnet current is decreased from a chosen starting value to another chosen final value. The time spent during this current drop is inversely proportional to the total power absorbed. By comparing two such demagnetization times, one with a constant additional power added via the heater, we determine the original power (without the heater). Using this approach, the heat conducted through the Kevlar legs into stage 1 (at 0.08 K) with the 4 K platform held at 3.1 K was determined to be 0.8 μW. This was an acceptable value, although somewhat higher than the predicted 0.33 μW. It is possible that the extra power might have a different source, such as vibration heating in the Kevlar. We also characterized the performance of the superconducting heat switch. When open, it conducted 4.6 μW from stage 2 at 0.3 K to stage 1 at 0.08 K. This matched the predicted conduction through its Vespel support and the superconducting lead.

A different method was used to measure the superconducting switch's closed conductance. We controlled stage 2 at 0.05 K and fixed the current in stage 1's magnet. We then applied three different heater powers to stage 1, each time waiting until its temperature stabilized. The slope determined from a linear fit of power vs. ΔT indicated a closed switch conductance of 6 mW/K. This parameter serves as a figure of merit for the switch.

PATH FORWARD

The pre-vibration testing of the CADR is now complete. The superconducting heat switch will be removed from the system and subjected to a vibration test in late July, 2023. It will later be re-installed in the CADR, and its closed conductance at 0.05 K will be compared to the pre-vibration value. The same vibration campaign will include a separate test of a mass/moment simulator of a suspended stage 3 salt pill and heat switch. This assembly, which includes Kevlar legs identical to those in the CADR, has been thermally cycled 18 times between room temperature and 17 K. After these cycles the suspended mass remained centered in its suspension frame. If it survives the vibration test, this suspension design will be a viable candidate for future space missions.

Before re- testing the CADR, we plan to enhance the thermal connection between stage 4 and the mechanical crycooler. Hopefully that will allow us to demonstrate at least 6 μW of usable cooling at 0.05 K. We will also try to determine the cause of CADR underperformance when cooling below 0.05 K. After that, the system will probably be kept intact as a test bed. We have identified several possible component upgrades which may be implemented. Replacement salt pills for stages 3 and 4 could contain yttrium barium gallium garnet (YBGG) and gadolinium lithium fluoride (GLF) respectively. The stainless steel gas-gap heat switch shells could be replaced by ones made of titanium 15-3-3-3. A new superconducting heat switch could be made using ultra-pure annealed copper parts, and a replacement stage 1 copper linkage could easily be designed to have a larger effective area/length ratio. Any of these changes would be easy to implement and would almost certainly improve the CADR performance.

CONCLUSION

The 4-stage CADR has cooled close to its target specifications, and we are hopeful that additional strapping will allow us to demonstrate the target cooling power at 0.05 K. A next-generation 5-stage CADR is being designed using lessons learned from this effort.

ACKNOWLEDGEMENTS

The development of the CADR was supported by NASA's Strategic Astrophysics Technology program.

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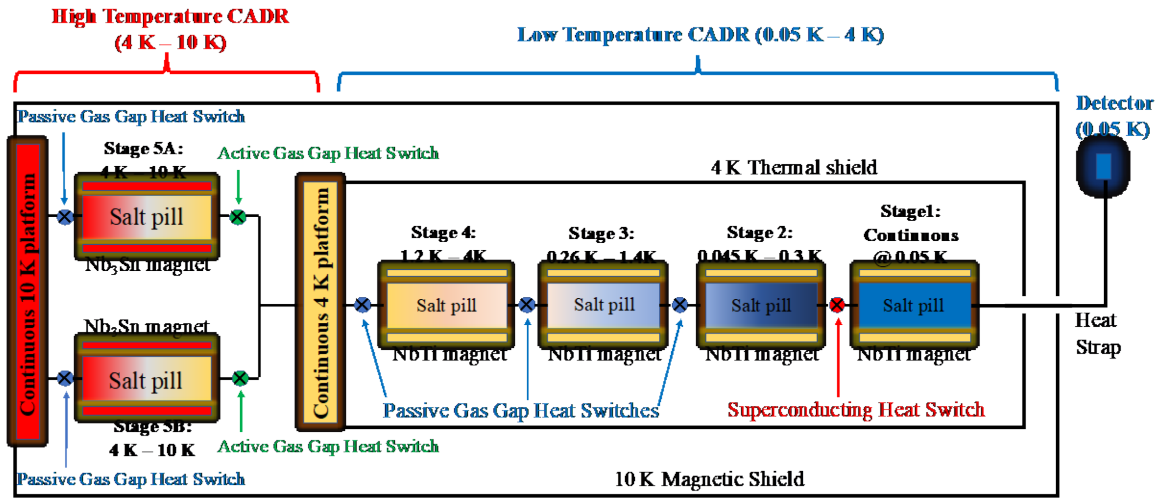


Figure 1. A schematic representation of the original 10 K – to – 0.05 K CADR design.

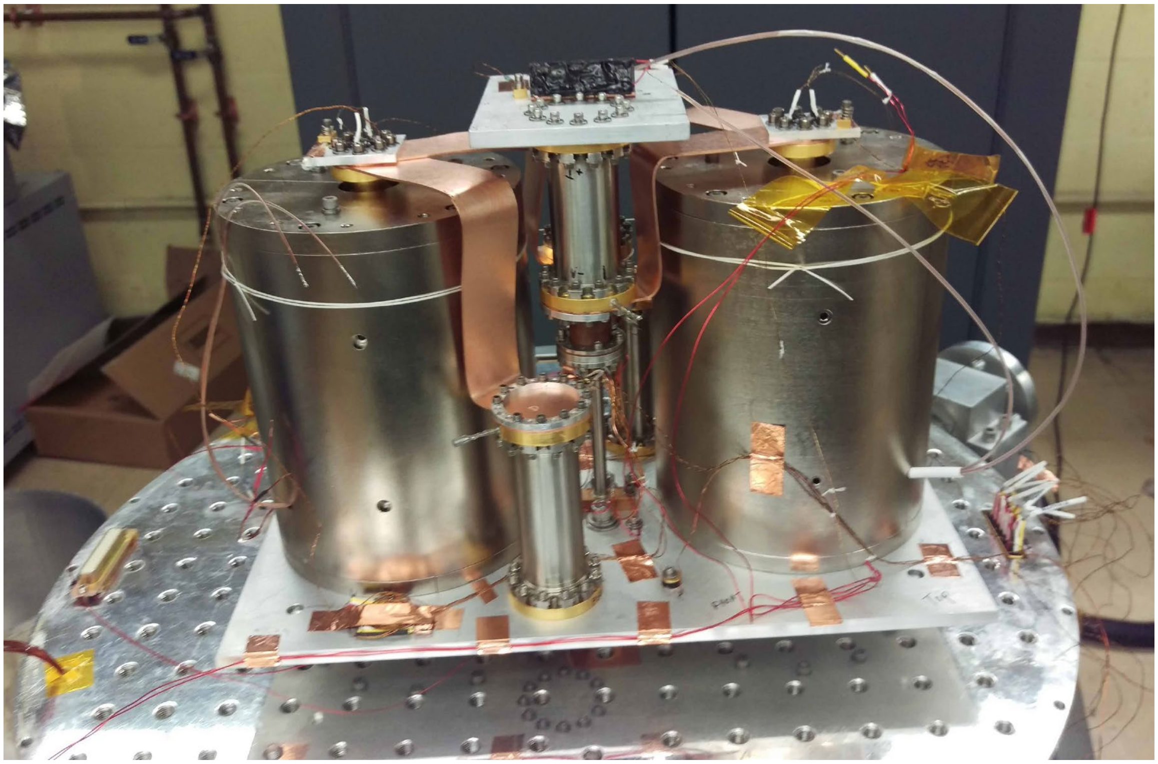


Figure 2. The 4 K – to – 10 K CADR installed in a cryostat for testing. This subsystem was eventually shelved due to limited resources.

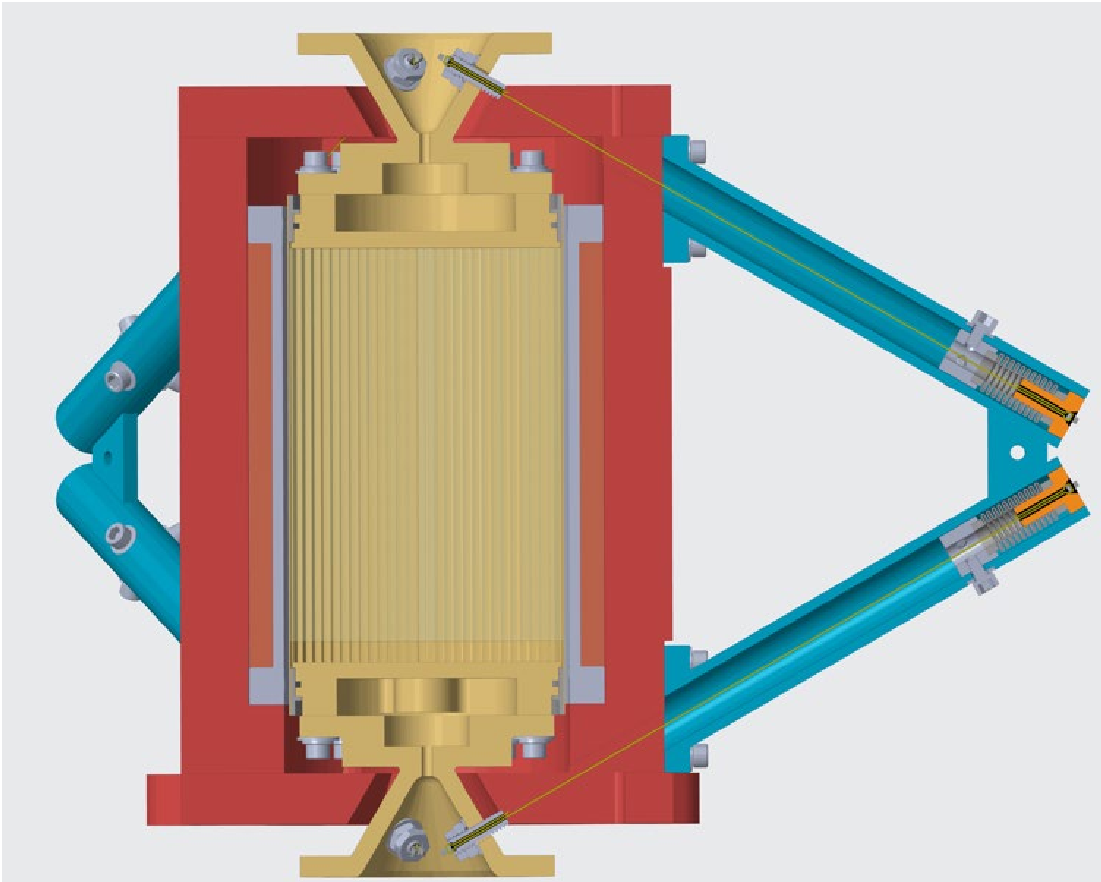
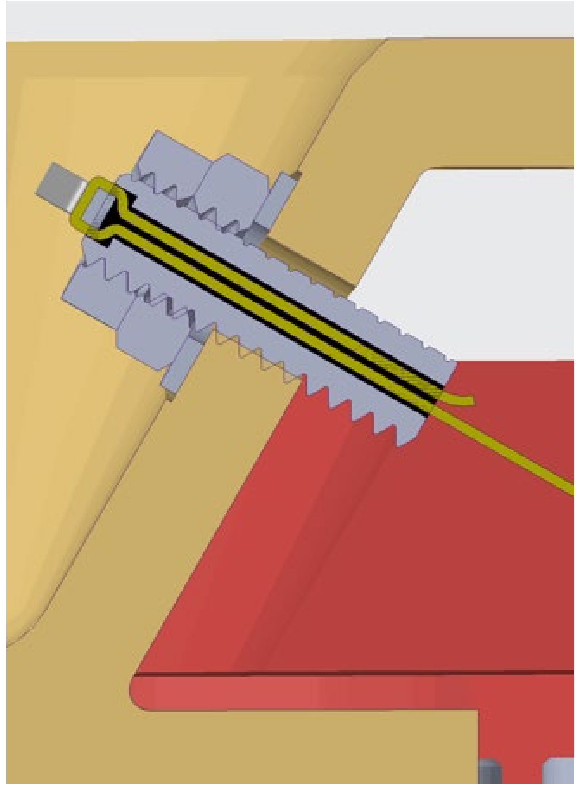


Figure 3. A cross section image of stage 2 or 3. The salt pill assembly is suspended by six tensioned Kevlar legs. Each leg extends out through the magnet shield to the far end of a steel tube, where it bears on a compression bellows.

A)



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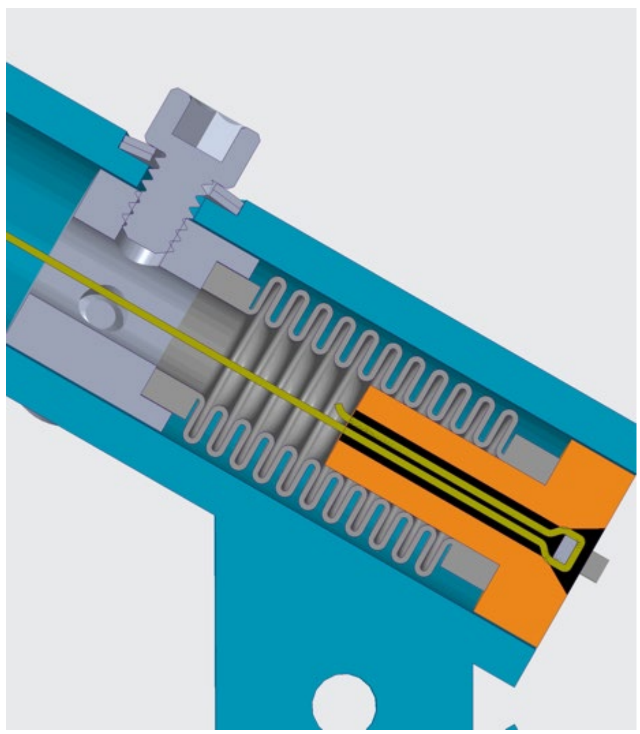

Figure 4. Details of two ends of a Kevlar suspension leg. A) The inner end feature a threaded rod and tensioning nut, which bears on the salt pill assembly. B) The metal part at the outer end bears on a calibrated compression spring.

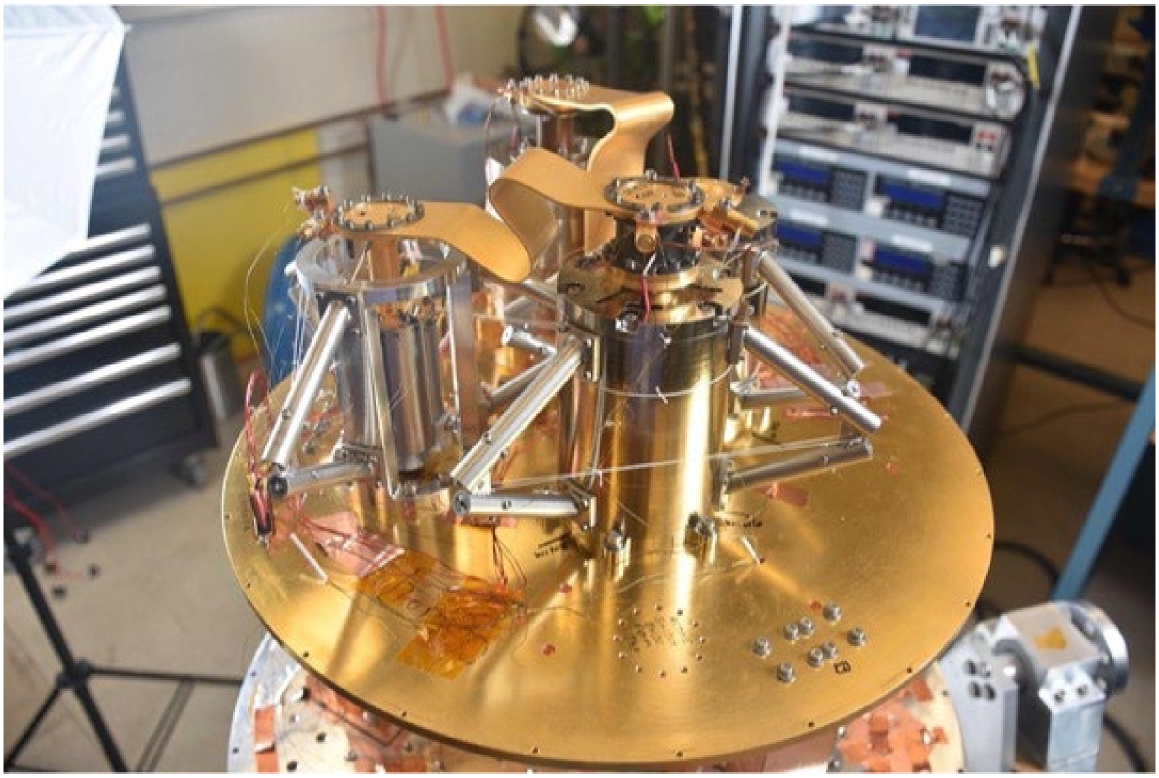

Figure 5. The 4 K – to – 0.05 K CADR installed in a cryostat ready for testing.

HIGHLIGHTS

- We built a designed-for-space-flight 4-stage CADR
- Our CADR provides 5.4 μW of cooling at 0.05K, rejecting heat to 4.0 K
- The CADR's superconducting heat switch will soon be vibration-tested
- A mass simulator using the CADR's Kevlar suspension will also be vibration tested