Multidisciplinary Senior Design

P20129 F.R.O.H.S.T. Technical Paper

Flight-Ready On-board Heat Switch Technology

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Abstract:

In order to detect remnants of the creation of the universe within the depths of space, a sensory package must have very little noise. To minimize such noise, the sensors must be extremely cold, which requires a refrigeration system to dissipate heat. An adiabatic demagnetization refrigerator, referred to as an ADR, is such a system. The motivation behind this project is to assist the RIT Center for Detectors in the construction of an ADR by proving that the mechanical portion, the heat switch, can operate reliably at cryogenic temperatures, specifically lasting at least 1000 cycles at 2 Kelvin. This variant of heat switch will be smaller than pre-existing heat switches from the 2018-19 team P19129, resulting in the challenge of miniaturizing the technology. They created a lab prototype that had low durability and used ferrous materials, which interfere with the ADR. The main focus of this project has been to revise the design, finish testing, and to make the system flight ready. However, given the events that transpired due to the COVID-19 pandemic, the team was unable to finish all the tasks. The design was reviewed, modifications were made, the prototype was assembled with the debugging process started, and the new flight-ready electronics were designed. The purpose of this paper is to outline the design, manufacturing, assembly, and testing of the flight-ready heat switch design created by team MSD P20129.

Background / Motivation

Measurements of astrophysical electromagnetic radiation at far-infrared wavelengths require detectors that are cooled a substantial way to absolute zero temperature. In order to attain such low noise, the sensors must be as cold as physically possible; cold enough to prevent any latent heat emissions from interfering with the measurement of deep-space signals. In order to cool the sensor, an adiabatic demagnetization refrigerator (ADR) is used. The ADR is composed of a solid salt crystal, referred to as the salt pill, which is surrounded by a magnet. The salt pill has two contact points: a sensory package on the top and a mechanical heat switch on the bottom When the magnet is activated, a magnetic field acts on the salt pill causing the particles within the salt pill to align. The alignment of these particles is an exothermic process that requires little energy which generates large quantities of heat that exude from the salt pill. The mechanical heat switch is in contact with the salt pill during this process so the exuded heat is transferred into a heatsink and not into the scenery package. Once the heat has dissipated into the heatsink, the heat switch disconnects from the salt pill and the magnetic field stops. Without the magnetic field acting on the salt pill, the particles begin to scatter as the salt pill returns to its original state. As the particles scatter, it causes an endothermic reaction that draws heat in from its surroundings. At this point, the sensory package comes in contact with the salt pill, resulting in the cooling of the sensory package due to the salt pill drawing in heat. This process is then repeated until the sensor package reaches an optimal temperature. When the ADR is combined with a cryostat filled with liquid helium, the sensory package can potentially be cooled to almost absolute zero, or 0.1°K, since heat is dissipated into the heatsink and the liquid helium. This project was created in order to design, construct, and test a mechanical heat switch that will be used in an ADR constructed by the RIT Center for Detectors.

Stakeholders

The primary stakeholders to this project include the customer Dr. Michael Zemcov and the RIT Center for Detectors, our guide Martin Pepe and the MSD department, and of course the team P20129. The astronomical community at large would also benefit from the successful completion of the heat switch and the data it enables sensors to collect. The machine shop is also a stakeholder since they must manufacture some of the parts.

Operating Environment

The heat switch is required to operate at cryogenic conditions which range from 77K, when utilizing liquid nitrogen, all the way down to the goal temperature of 2K when utilizing liquid helium. Additional requirements include enduring the vibrations and acceleration of a rocket launch and flight to the specified NASA Vehicle Level Two standard. The system has to maintain integrity throughout the process because failure would be catastrophic to the greater flight mission. Since this experiment will occur outside of earth's atmosphere the system must also operate in a vacuum.

Customer and Engineering Requirements

Throughout the first half of MSD I, meetings with the customer continued to shape the expected customer requirements and, therefore, engineering requirements. There were four very important customer requirements. First, the device must fail 'open,' as in, the system should not contact the endothermic crystal. Second, the system must reach the desired thermal conduction value. Third, the heat switch must be robust enough to survive the NASA Vehicle Level Two specification and operate a minimum 1000 cycles. Fourth, the system must utilize non-ferrous metals in order to avoid interfering with the ADR. Additional requirements include fitting within the provided volume and utilizing minimal digital signals to control the heat switch and receive feedback indicating the switch position. Budget was also a large constraint both from a customer and engineering perspective as anything certified to operate in cryogenic environments is well out of the price range of the project.

Mechanical Design

The Ledex rotary solenoid was chosen due to its ability to transmit the necessary torque at the target system voltage while having minimum controls. The other benefits are that it was relatively low cost, and when combined with a ratchet mechanism, would allow for an actuation system that would have no excessive current draw over the large periods of time during which the system is active. The solenoid housing was designed from 6061-T6 aluminum alloy for the specific strength and ease of machining as well as the price per pound of raw stock. The housing incorporates the mounting screws that are a part of the solenoid assembly and holds the solenoid off of the mounting fixture to reduce any heat transfer from the solenoid heating up under load.

A pair of ratchets transmits the torque from the solenoid to the cam. The teeth geometry is such that the torque is transmitted only in the clockwise direction. Therefore, the system will not return to its original state on the backstroke of the solenoid. A second housing surrounds both ratchets, keeping them in alignment, while serving as the upper restraint for a return spring which helps reset the solenoid after it is pulsed. A quad cam opens and closes the arms contacting the salt pill as the cam rotates in 45-degree increments. The design is such that the system alternates between open and closed allowing for the solenoid to be pulsed rather than continuously powered.

A pair of thin copper arms opens and closes on the salt pill. The arms pivot about small flexural pivots, which were chosen due to their compact footprint compared to bearings. The flexural pivots, along with an extension spring attached to the back end of the arms help return the arms to open position when the cam is in the open position, and provide force on the cam that holds the system closed between cycles. A pair of rounded aluminum blocks is attached to the arms by socket head cap screws, and interfaces with the cam. Their rounded shape facilitates the rotation of the cam.

A pair of pins is held into the front end of the arms via set screws. These pins are part of the heat path and come in contact with the salt pill when the system is closed. They are adjustable in and out to allow for different salt pill sizes. Flexible braided copper wires complete the heat path by connecting the arms to the heat sink below. The wire is clamped beneath the bottom of the arms and to the top of the sink. It is flexible to allow the arms to move between the open and closed states.

Electrical Design

The electrical design for control of the heat switch is relatively simple. The major electronics deliverable was to be able to control the heat switch with one digital signal line and provide a digital signal indicating the state of the heat switch. The control was achieved by utilizing an Omron relay and feedback signal using a micro-switch mounted to the heat switch assembly. Given the extreme temperature changes of the operating environment of the solenoid, the coil resistance changes as well. It was determined that stepping the rocket supply voltage down from 24V to 9V was vital to meet our 13-watt activation target. To accomplish this voltage shift, a LM2596 DC buck converter, with the required passive network, was utilized.

The lab testing electronics were not as simple. The test system required four main elements to determine the effectiveness of the heat switch. The first was precise control of a thermal load to 100mW range to simulate crystal heat load during the exothermic reaction to allow a microcontroller to modify the output voltage. The LM2696 was also used here in conjunction with an AD7376 10KΩ digital potentiometer contained in the current feedback network of the buck converter. The AD7376 features 128 resistor taps to enable the max theoretical precision of 39 mW. A more realistic one LSB of noise was accounted for, leaving the thermal load to reach 78 mW precision. A similar adjustable power supply was adopted to enable room temperature testing of the heat switch when the resistance is not lowered by the cryogenic temperatures. The third element was data collection to verify the mechanical reliability of the system. The data collection utilized the SD card to write successful open and close cycles with a timestamp relative to the start time of the test. The final element required communication over the serial UART port on the

Teensy to communicate with the cryostat temperature monitor, through a Linux machine in the middle.

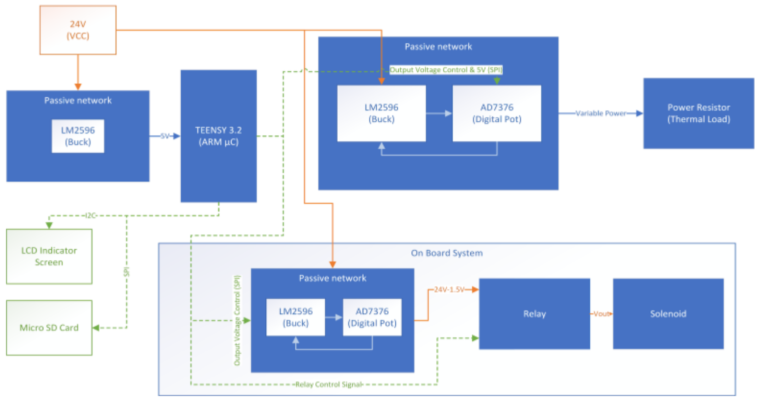

Figure 1: Lab test system PCB Block Diagram

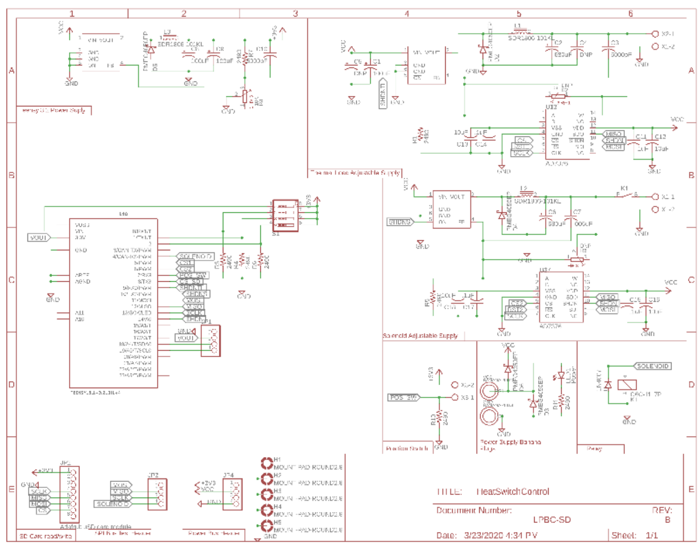

Figure 2: Lab test system PCB Rev-B

Material Selection

The materials chosen for parts varied depending on its use. For components that were part of the heat path, 110 copper was used. While there are purer forms of copper that can be used in high conductivity designs, this was mainly for heat transfer purposes so the minimal difference in thermal conductivity between the two alloys was not worth the extra cost and lead time. The rest of the assembly was made from various aluminum alloys for their non-ferrous properties, machinability, and low price per pound. The ratchets being high wear items were made from 7075-T6 alloy for its greater hardness and specific strength in comparison to the standard 6061-T6 aluminum. All other components used 6061-T6 for its lower cost per pound compared to 7075-T6. Screws, nuts and washers were all of 316 stainless steel, as to not be magnetic or easily magnetized.

Manufacturing and Solenoid Modifications

All of the manufacturing for this project was done on campus at the RIT Mechanical Engineering machine shop. Most parts were billet machined by either a team member or submitted to the shop as a work order request. Many of the components were complex in design and required many CNC operations which would be costly if sent out to a manufacturing company so keeping them to in-house manufacturing was critical to ensure the budget would not be exceeded. There are several places where slight redesign could benefit manufacturability especially regarding the number of machine setups needed for each part. Due to time constraints and the bandwidth of the shop and team members, many parts did not have spare parts machined.

In order to increase the reliability of the purchased rotary solenoid there were many modifications made to the original purchased component. The thin sheet metal housing was pressed off to reveal a felt pad. This was removed from the assembly along with the housing. The small circlip that holds the shaft in place was then removed in order to disassemble the shaft, ball bearings, and gain access to the internals for deeper cleaning. The entire assembly was then deep cleaned using isopropyl alcohol and the Sonicator in the lab. At this point the shaft was drilled with a cross hole for the M2 screw that goes through it and the bronze/brass bushing was drilled out by Ø0.002 from the current dimension. Once all the components were modified and cleaned again, a dry powder lubricant was added to the region where the ball bearings ride on the shaft and in the space between the shaft and bushing.

Design Verification

In order to guarantee that the mechanical heat switch is able to survive the volatile environment of being launched into space as well as to not damage the ADR salt crystal in flight, the heat switch had to be compliant with the NASA Vehicle Level Two standard. This standard requires that the heat switch withstand a frequency range of 5-2000 Hz and an acceleration range of 1.5 to 10 g’s without it disassembling in flight or contacting the salt pill. Using a vibration tester in the CfD lab, a newly constructed vibration mount is bolted to the plate of the tester. The mount allows for the mechanical heat switch to be oriented along the thrust axis, having the arms facing upward, as well as any horizontal or vertical axis.

ANSYS Static Structural Analysis

ANSYS static structural analysis was conducted in order to assess the minimum safety factor of the assembly when subjected to the static loading described in the NASA Vehicle Level Two acceleration. All fasteners were set up as bonded joints with anything free moving being set to frictional contacts for this analysis. The acceleration loading was a worst-case axial and thrust loading per the NASA Vehicle Level Two reference. The results of the analysis showed that no component is even close to the structural margin. The minimum safety factor on any component based on this static loading was 9.5 with the highest loaded point being the copper arms themselves, as seen below.

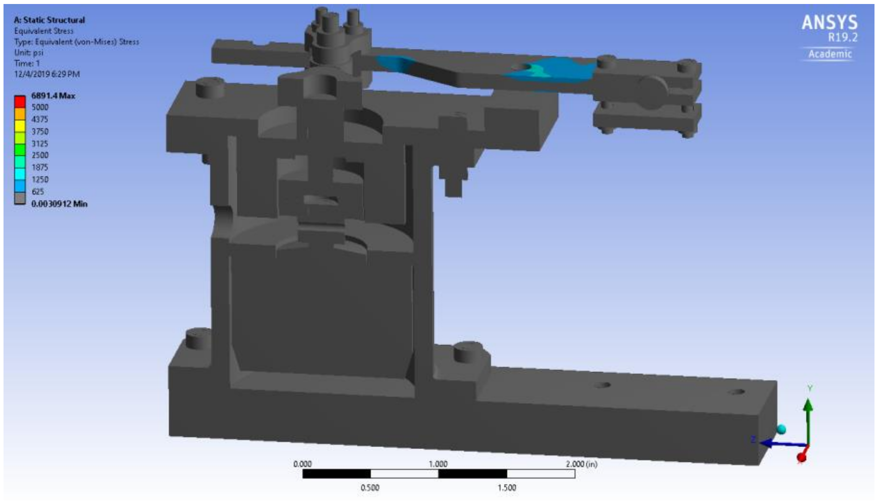

Figure 1. Results of static structural analysis showing equivalent (Von Mises) stress

ANSYS Thermal Analysis

ANSYS thermal analysis was conducted in order to assess the thermal capabilities of the system at all three ambient temperatures of interest per customer and engineering requirements. The simulation was run in an environment with low emissivity and no convection due to the ADR existing in a vacuum environment. The simulation was run with multiple thermal loads applied at different ambient temperatures. The results from this simulation not only show theoretical performance at these temperatures but also can be used to assess where the heat flux is highest and lowest. This reflects why the device's performance would drastically increase with the addition of electron beam welding the copper braid to the arms/pins rather than using fasteners and frictional connections. The results of the simulations can be seen below in Table 1 and Figure 2.

Thermal Analysis Results								
Column1	Power [W]	Base Temp [K]	Max Temp [K]	Temp Delta [K]	Resistance [K/W]	Conduction [W/K]	Customer Requirement [W/K]	Difference
Run 1	2.5	293	300	7	2.64	0.38	0.01	3688%
Run 2	5	293	306	13	2.66	0.38	0.01	3665%
Run 3	2.5	77	84	7	2.67	0.37	0.01	3650%
Run 4	5	77	90	13	2.67	0.37	0.01	3650%
Run 5	2.5	4	11	7	2.67	0.37	0.01	3650%
Run 6	5	4	17	13	2.67	0.37	0.01	3650%

Table 1: Results of thermal analysis and compliance to customer requirement

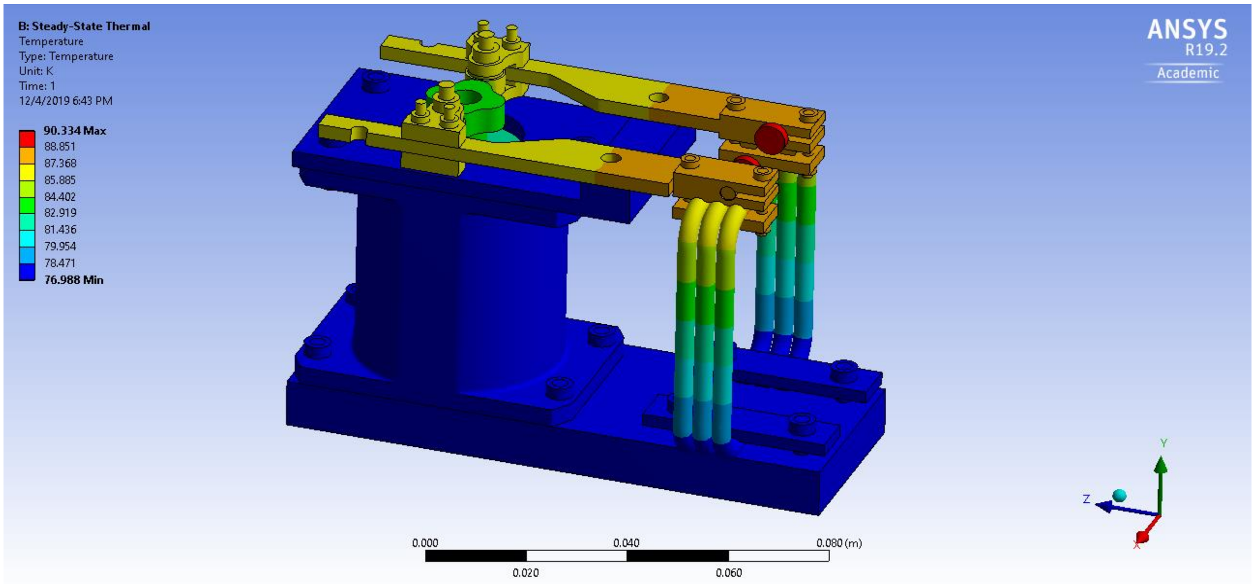

Figure 2. Plot of temperature from ANSYS thermal analysis run at 77K baseplate temperature.

ANSYS Modal Analysis

ANSYS modal analysis was conducted during the detailed design phase to assess the harmonic response of the structure. The entire assembly was taken from Solidworks and put into the ANSYS modal analysis workbench where every bolted connection was modeled as bonded and any free moving parts modeled frictional. The results of the analysis clearly show low natural frequencies in the directions where the arms are free to pivot, thus essentially becoming spring-mass systems with a low natural frequency. There were other modes that had a higher natural frequency in other directions where the arms were not free to simply pivot. The results from the modal analysis can be seen below in Figure 3.

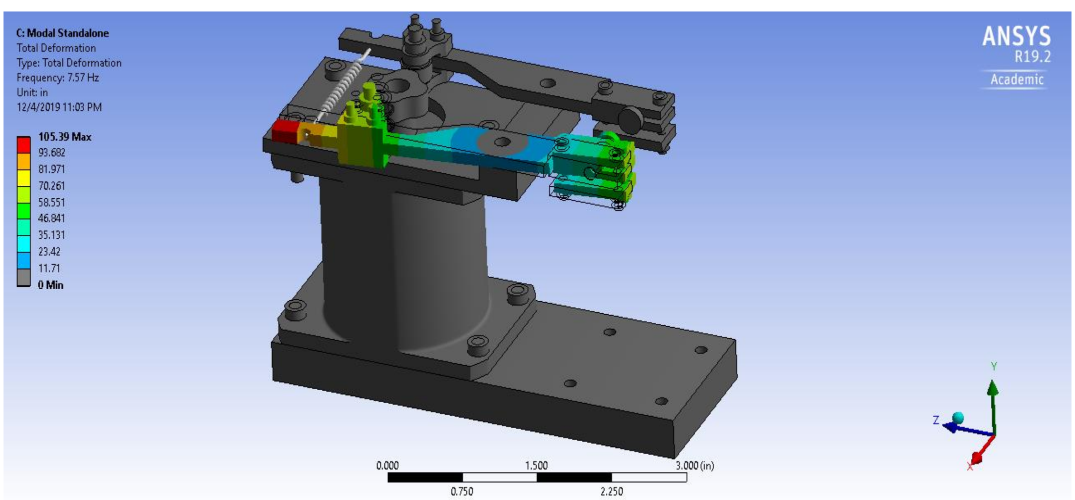

Figure 3. Results from modal analysis showing the first mode of 7.95 Hz.

Switch and Spring Analysis

Added to the design was a switch that would determine the state of the heat switch. It was then verified that the switch would not impart enough force to stop the arms from closing, using equations derived from Newton's First and Third Laws, the definition of torque and Hooke's Law.

$$F_{switch} = \frac{F_c y_c - F_{sp} y_{sp} - k_f \Delta\theta_a}{y_{sw}}$$

$$F_{cam} = \frac{\tau_s}{d_c} cos(\theta_c)$$

$$F_{spring} = k_{spring} \Delta x_{spring}$$

Servo Torque	τ_{sw}	0.6000	lbf*in	Change in Arm Angle	$\Delta\theta_{arm}$	0.408	degrees
Pivot-Spring Distance	y_{sp}	1.99	in	Change in spring length	Δx_{sp}	0.034	in
Pivot-Cam Distance	y_c	1.404	in	Spring Force	F_{sp}	0.009	lbf
Pivot-Switch Distance	y_{sw}	0.4317	in	Cam Force	F_c	2.639	lbf
Exension Spring Rate	k_{sp}	0.26	lbf/in				
Flex Pivot Spring Rate	k_f	0.0035	lbf*in/degree	Max allowable switch forc	F_{sw}	8.539597	lbf
Servo Moment Distance	d_c	0.214	in	Switch Force		0.1	lbf
Cam angle	θ_c	19.721	degrees	Margin		84.39597	-

Table 2. Max allowable switch force results

Early testing of the previous prototype indicated that the ratchet return spring was likely too stiff for the solenoid to fully overcome. Therefore, a new spring was selected using several requirements. The new spring had to have a softer spring rate than the previous iterations, while having less preload and minimum internal diameter greater than 0.170 inches to accommodate the increased diameter of the ratchet shaft. This led to the selection of a 9.5 mm long, 4.5 mm internal diameter 302 Stainless Steel spring with a rate of 0.29 lbs/mm.

Results and Conclusions

The outcome of these design, fabrication, and testing efforts has been a heat switch that while similar in fundamental design as the predecessor, has gained many improvements both in mechanical design and fabrication as well as electronics. While there are more modifications that need to be made to the system for maximum reliability and performance in future years, there has been great strides made to characterize the performance and reliability of the current actuation system as well as a large list of improvements and performance-enhancing modifications that can be carried out by future teams.

Given the events that transpired during/after spring break in relation to Covid-19, the decision was made to immediately stop all protype work conducted in the lab and cease any testing that was in progress. The remainder of the project has been devoted to updating the documentation relating to the electrical and mechanical design as well as creating additional documents outlining future work and current inventory for further development of this product by future groups.

Future Work

For reasons outside of the team's control the project is unfinished. For extensive detail on the recommended improvements and future work please see *"P20129 Design Manual"*. There remain several things to improve and fix from the latest prototype. First the cam and ratchet needs to be updated to improve the functionality of the ratcheting mechanism. After this is completed vibration testing can commence which will likely lead to another round of improvements. Once the system passes the vibration testing, E-beam welding and gold plating can be done to improve thermal conductivity of the system. After this, the final thermal performance testing can be achieved. On the electrical end of improvements, Rev-B of the lab test PCB should be ordered and populated. From there, the software must be validated with the modified hardware configuration.

Acknowledgements

Senior design team P20129 would like to extend our gratitude to the many resources that made this project possible. The original heat switch concept was designed by Grant Wilson in his 1998 research paper on the topic. Thanks to the help of Professor Carlos Barrios and Bryce Salmi for their time and recommendations on improving the electrical system. Thank you to the KGCOE Machine Shop team for providing machining assistance and machine time to make this design a reality. Senior design team P19129 was very helpful in the transition phase of the project and provided ample materials for reference. Graduate students Chi Nguyen, Lazar Buntic, and Dale Mercado were very helpful with becoming acclimated in the lab and with cryogenic experiments. Our customer Dr. Michael Zemcov has also acted as an invaluable resource for the team as a subject matter expert and an excellent customer to work for. Lastly thanks to Martin Pepe for guiding the team through the engineering processes and instilling some of his years of engineering knowledge into us during our last academic engineering experience. This paper was a team effort by Steven Donovan, Jacob Lawson, Matthew Davern, Christopher Canon.

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