

Design and Testing of the CubeSat Form Factor Thermal Control Louvers

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ABSTRACT

As CubeSat and SmallSat missions increase in complexity and power consumption they present innate thermal challenges. Science instruments may require thermal stability while a variety of factors such as high-powered components, sunlight and shadow on orbit, or tight spacecraft layout may produce a wide range of temperatures. The CubeSat Form Factor Thermal Control Louvers are a passive method of stabilizing the thermal environment inside of small spacecraft via miniature thermal louvers. These louvers are a patented design, with a technology demonstration version of the louvers operating correctly in flight on the Dellingr CubeSat in 2018. This paper will describe the methods used to develop and test this technology, as well as the results obtained and how this technology may be used in CubeSat and SmallSat missions.

INTRODUCTION

The CubeSat Form Factor Thermal Control Louvers (here forward known as CubeSat thermal louvers) address the need for better thermal control on CubeSats with temperature-sensitive components onboard. The CubeSat thermal louvers will narrow the range of temperatures experienced by internal components without expending power, as the thermal louvers are a means of passive thermal control. During two years of technology development, the CubeSat thermal louvers were subjected to life testing, thermal vacuum testing, vibration testing, and finally prototype testing in space. The technology has now been patented and the flight of an experimental version of the CubeSat thermal louvers aboard the Dellingr mission has raised the Technology Readiness Level (TRL) of this technology to TRL 7.¹

DESIGN BASIS

The CubeSat thermal louvers were modeled off of the large thermal louvers designed for missions such as Magellan, Viking-1, GOES, and TRMM.² These larger missions utilized the passive thermal control of large banks of louvers, carefully controlled by tuned bimetal springs. Louvers in these larger spacecraft were up to several feet long, controlled by at least one tuned bimetal spring per flap.

Bimetal springs are made of two metals with different thermal expansion coefficients fused together. When heated, one metal expands more than the other metal, creating predictable, repeatable movement. The choice of a spring coiled shape increases the range of movement, creating the ability to rotate a flap with a change in temperature.

Components can radiate or conduct heat to the spring interface which activates flap movement, or an external environment can change the temperature of the bimetal spring and induce movement. As the temperature decreases due to radiative cooling, the spring returns to its original position closing the flap and conserving heat. Thus the thermal louvers are useful in passively maintaining a set temperature within certain limits.²

Similar Work

At the time of funding there had been some prior effort to create thermal louvers for CubeSats. A MEMS Louver system was devised by Johns Hopkins University's Applied Physics Lab (JHU/APL) for use on CubeSats. These louvers were microminiature arrays, with flap width in the micrometer range. 400 louvers fit within a square centimeter and were actuated by electrostatic linear motors. Because of the linear actuators, these arrays were not passive.

There was a similar invention by William Trimmer patented in 2001 entitled "Micro Louvers for Cooling Satellites." This patent used a shape memory alloy or similar to curl up an entire surface coating of the spacecraft to reveal a different emissivity coating underneath.³

Several designs for passive thermal control for CubeSats have come into existence since the initial research was done for the CubeSat Thermal Louvers. Tailored emittance coatings on radiators, for example, were used on the IceCube CubeSat, a NASA Goddard Space Flight Center satellite mission launched in 2018.⁴ Deployable radiator panels, CubeSat sized heat pipes, and phase change materials are all in development for the CubeSat

customer.⁵ A surface covering was devised by researchers at the University of Patras which changed surface emissivity using ultralight patterned surfaces. These surfaces transformed from 2D to 3D geometry based on temperature.⁶

The field of miniaturized thermal control for CubeSats continues to grow, and the CubeSat Thermal Louvers are one of several passive thermal control methods which will most likely become available in upcoming years of CubeSat space flight.

A benefit of the CubeSat Form Factor Thermal Control louvers is that they are modular, meaning that they can be re-sized for different sizes of CubeSat, or even partial coverage of a surface, with minimal re-design and lower cost than methods which require comparable size tailoring. In addition, they are based off of a larger pre-existing technology, which accelerated the development of these louvers.

DESIGN DESCRIPTION

The CubeSat thermal louvers were designed to be unique in three ways: their miniaturization of a larger technology, their method of manufacture, and their modular design.

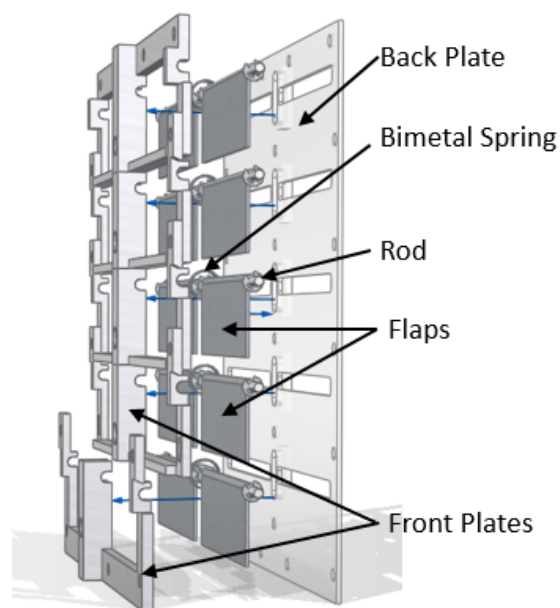


Figure 1: Exploded view of the 1U sized CubeSat Thermal Louvers

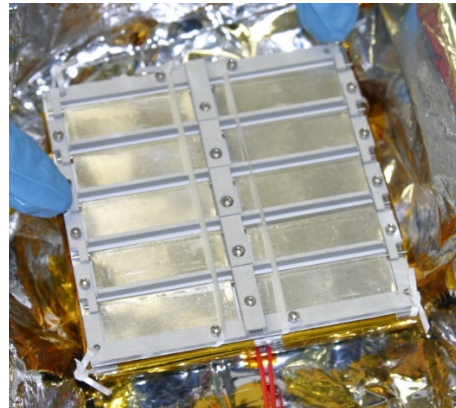


Figure 2: Assembled Front View of the 1U sized CubeSat Thermal Louvers

The miniaturization of the CubeSat thermal louvers required finding a bimetal spring which would have the force and rotational movement required to actuate the louver flaps, yet be small enough to fit on the side of a CubeSat. Once this bimetal spring was selected, the rest of the louver system could be designed around it.

Flaps were attached to a metal dowel rod and made of sheet metal to lower the mass of the flaps. With a lower mass, the louver flaps were not damaged during random vibration and did not add significantly to the mass of the CubeSat. Both traits were desirable for the design. The flaps could have been polished or painted with a coating to obtain the emissivity desired; however, they were left with their original sheet metal finish for these tests.

The back plate was where the bimetal springs were mounted, and could potentially be built as the structural side panel of a CubeSat. For the demonstration and testing units, though, the back panel was a stand-alone 1U sized aluminum plate painted with a high emissivity Z93 white coating. The bimetal springs were epoxied into small indentations milled into the plate to lower the height of the spring. The back plate, in spacecraft use of the thermal louvers, would have hot internal components either radiating or conducting to it to transfer heat to the bimetal springs.

The front plate miniaturization led into the second way in which the CubeSat Thermal Louvers were unique: their method of manufacture. The front plates were too thin to be manufactured via normal machining without raising the cost by a significant amount. Therefore, it was determined that the front plates would be manufactured using 3D printing. Several iterations of 3D print materials were introduced before Ti64 titanium front plates were decided upon as the 3D printed material of choice.

The resulting 1U louver series fit into a 1U area; however, it did not account for the rails which are keep-out zones on some deployer-launched CubeSats. The spring casing on the front plate in the test design also did not fit within the 6.5 mm limit on some rail deployers, which would limit the use on 1U CubeSats, though other, larger CubeSats may have alternatives to a rail deployment. Future design adjustments may bring the spring casing lower to fit within 6.5 mm.

To encourage ease of transition from 1U to any other size of CubeSat, the third element of unique design came into play- the modular design of the CubeSat thermal louvers. Each set of louvers had one top front plate, one bottom front plate, and then as many middle front plates as were needed to chain together to cover the desired area. The back plate was the only part of the CubeSat thermal louvers required to be custom-made for each set of louvers. The other thermal louver components, bimetal springs, flaps, rods, and front plates, were interchangeable between systems and so could be ordered in bulk and used as needed. This greatly reduced the manufacturing time and cost of the thermal louvers.

DEVELOPMENT

Development of the CubeSat thermal louvers prototype included the machining of the mechanical parts, deposition of thermal coatings on the back plate, and assembly of the 1U louver system.

Materials

Several iterations of 3D printed materials were used for the front plates. All materials selected were low outgassing, below the NASA recommendation of 1.0% Total Mass Loss (TML) and .01% Collected Volatile Condensable Material (CVCN).⁷ This narrowed the search down to a few materials. Initial assembly was done with finite deposition modeled Ultem 9085, which was determined to have too rough of a surface for the rods to turn smoothly while actuating the flaps. Nylon 12 Glass Filled (GF) was less rough, having been printed using a laser sintering method; however the material was not conductive, which meant that it would potentially create grounding issues for the spacecraft.

The next iteration included Nylon 12 GF with an aluminum deposition coating on it. This made the material conductive but the material was still relatively soft and there were issues with the recommended torque for a CRES-300 #2-56 screw causing indentations in the material, thus losing pre-load on the bolt. Washers were added underneath of the bolts which solved this problem. It might be possible to use Nylon 12 Aluminum Filled (AF) material for the front plates, which would make them electrically conductive, but that material was not tested.

The Ti64 titanium material was settled on for the final design because of its higher yield strength and smoother surface finish. The Ti64 front plates were laser sintered and polishing was an optional surface finish for 3D printed metal components which made the surfaces smoother than the Nylon 12 GF material. In addition, Braycote lubrication could be added without soaking into the material, which aided in reducing friction further between the rod holding the louver flaps and the groove in the front plate where the rod rests.

Manufacture

The front plates were 3D printed, however the back plate was machined out of aluminum. To apply the high-emissivity coating to the back plate, areas covered by the front plate metal were masked to maintain metal-to-metal contact for grounding, and the remaining areas were coated with a Z93 white paint.

The louver flaps were made from 0.04" thick aluminum sheet, cut to size, and then a jig was used to fold them into the correct shape to slide onto a metal dowel rod. The dowel rod served to transfer motion from the coiling or uncoiling bimetal spring into angular motion of the flaps. The flaps slightly overlapped the front plate to prevent them from vibrating against the painted back plate during vibration.

The bimetal spring, essential to the functioning of the entire system, was a piece which also required significant refinement in order to find one that both fit the envelope and functioned properly in 1 G (Earth's gravity). Although the flaps were meant to operate in space, the thermal testing environment for the spacecraft was on the ground, so the spring needed to exert enough force to open the flaps fully in Earth's gravity.

The spring was procured from Crest Manufacturing, Inc., a bimetal spring company which agreed to make customized bimetal springs in an extremely small size. The springs were made of P675R bimetal and measured approximately a quarter inch in diameter.

More details on the design and manufacture of the CubeSat Form Factor Thermal Control Louvers can be found in their patent, patent number US9862507.¹

ANALYSIS

Bimetal Spring Deflection Analysis

Analyses were performed to determine which bimetal spring would provide maximum deflection in the estimated operating range.

There were two initial materials which could potentially function as needed for the thermal louvers. One was a

material called B1, the other P675R. Both had relatively high flexivity values in the range of temperatures that the thermal louvers would be operating in. Flexivity values were provided by the manufacturer, Crest Manufacturing. These bimetals were found to be used by several vendors in industry.⁸

The flexivity of P675R was higher over the selected temperature range compared to B1's flexivity across the same temperature range.⁹

Angular deflection of the flap when rotated by the uncoiling bimetal spring was calculated using information provided by the manufacturing representative to determine the optimum length and thickness of the spring's bimetallic strip.⁹ Also taken into account was the maximum diameter of the spring coil, as it would need to fit in a CubeSat deployer.

The final design used a P675R spring coil. The manufacturer procured tooling which allowed them to create the .24" max spring diameter.

Sample springs were sent to determine whether a single spring would produce enough force to move a rod with a pair of louvers attached. The initial trial with a spring close to the final size and length was successful, which proved the design would function in ground testing.

Thermal Dissipation Analysis

An analysis was performed to determine whether the thermal louvers would dissipate enough heat from a CubeSat to justify their presence on the spacecraft. It was assumed that the louvers would be placed on a 6U face of a spacecraft with deployable solar arrays, filling the entire 6U side with as many flaps as possible. This quantity would be two columns of fifteen rows of flaps each. Every row has two flaps, so this would give a total of 60 flaps on a 20X30 cm area.

A derivation of the Stephan-Boltzmann Law was then used to calculate power dissipated from the surface of the thermal louvers.

$$P = \epsilon \sigma A (T_1^4 - T_2^4) \quad (1)$$

Where P is the power dissipated, ϵ is the emissivity of the surface, σ is the Stefan-Boltzmann constant, T_1 is the temperature of the back plate of the thermal louver assembly, and T_2 is the ambient temperature.

The emissivity of the surface was varied for three different cases. In the first case the surface was assumed to be a Z93 white painted aluminum panel with no front plates or louver flaps attached to it. The emissivity of this case was .92. In the second case the louvers were assumed shut, which was assumed to be similar to a

panel of buffed aluminum. The emissivity used in this case was .03. Finally, for the open louver case the white panel emissivity was multiplied by the fraction of white painted area shown by open louvers, with the remainder of the area assumed to be buffed aluminum, representing the front panels blocking some of the Z93 white painted emissive area. The emissivity for this case was .054.

$$\epsilon_{tot} = \epsilon_1 \frac{A_2}{A_1} + \epsilon_2 \frac{(A_1 - A_2)}{A_1} \quad (2)$$

where ϵ_{tot} is the total emissivity of the panel, ϵ_1 is the emissivity of the white panel, A_1 is the total area of the panel, A_2 is the white painted area revealed by the louver flaps, and ϵ_2 is the emissivity of the buffed aluminum.

The calculations were repeated for a 1U area with only 10 flaps, since this would be the size used in testing.

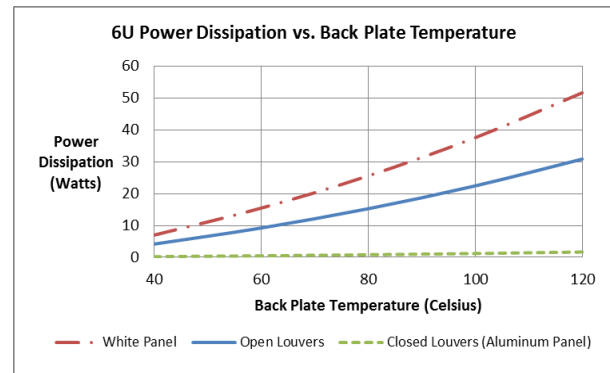


Figure 3: Calculated Power Dissipations vs Back Plate Temperatures, 6U Surface Area

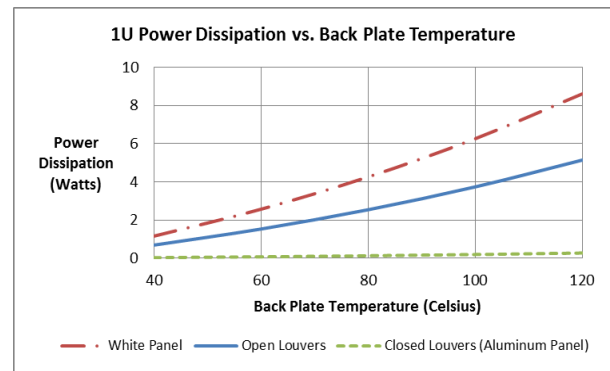


Figure 4: Calculated Power Dissipations vs Back Plate Temperatures, 1U Surface Area

This analysis showed that a CubeSat could potentially benefit from the heat dissipation difference caused by open vs closed thermal louvers.

TESTING

Testing endeavored to show that the CubeSat thermal louvers would perform well enough to advertise as a passive temperature control system. Tests included thermal oven testing to characterize the actuation of the bimetal spring, life testing to characterize the long-term repeatability of the spring movement, and thermal vacuum testing to verify the 1U heat dissipation analysis and flap opening angle at various temperatures.

Spring Characterization Testing

Several bimetallic springs, with rod and flaps attached, went through testing in a thermal oven both to ensure that they did not have excessive sideways movement as they changed shape and to prove that they could open the flaps against gravity. All springs performed well in both cases. They exhibited minimal lateral movement and were able to consistently and repeatedly change the flap angle over varying temperatures.

Life Testing

A 1U series of springs and flaps underwent life testing to simulate a full year in low Earth orbit (LEO). The life cycle testing resulted in over 12,900 cycles from fully open louvers (90° angle) to fully closed (0° angle) with no observable degradation in the performance of the bimetallic springs. The springs were cycled from 33°C to 55°C every ten minutes during the test using Kapton resistive heaters on the back plate of the thermal louver assembly. The heater was adhered directly to the back plate using Stycast, a thermal epoxy, and connected to a 24V power source, for 128 W of power on the heater. There was a slight gap where the heater did not touch the plate, since it needed to sit over the back plate's spring mount locations. These were recessed slightly into the back plate, extruding a square of metal out on the back side. The heater needed to bridge this extrusion, so not all of the heater face was in contact with the metal.

To record the life cycling, a monochrome camera took pictures of the setup every minute during the entirety of the life test. Photos were used to determine whether flaps opened the same way every time. In taking random samples of test cycles, it was concluded that they did open the same way consistently over the span of the life testing.

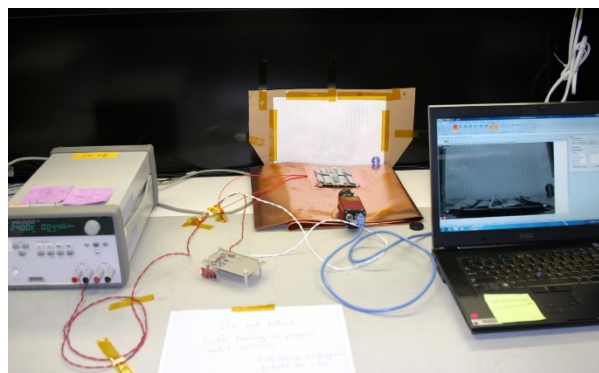


Figure 5: Life Testing Setup

1U Heat Dissipation Testing

A thermal vacuum test was performed on two modified 1U units: one with the flaps fully closed without the ability to open, and one with the flaps removed to simulate the best case scenario for flaps fully open. It is recognized that in reality there will be some flap shadowing in most cases, but because the analysis calculations did not account for shadowing, it was determined that the most accurate test would be with the flaps fully removed. The purpose of this test was to verify analysis and determine how much discrepancy there was between analysis and testing.

In the thermal vacuum test radiative heating of the louvers by the components inside of the spacecraft was simulated by heating a Z93 painted aluminum plate positioned about .25" from the thermal louver back plate. The radiative plate was heated with a 128W Kapton resistive heater epoxied to the radiative plate with Stycast.

The entire test assembly for each 1U set of louvers was enclosed on five sides in a "doghouse"- a reflective mylar thermal blanket with several layers, which simulated the isolated, enclosed area inside of a CubeSat. The louvered surface faced a cold plate, which simulated being exposed to the space environment.



Figure 6: Thermal Vacuum Setup for 1U Heat Dissipation Test

Each test run had a different cold plate temperature, representing different space environments. The cold plate was allowed to soak until the temperature change of the cold plate thermistor was $\leq 2^\circ\text{C/hr}$ to stabilize the temperature of the chamber. The heaters were then turned on and set to temperature. The Kapton heaters were controlled by a PIV controller and thermistor located on the front of the radiator plate, with a heater setpoint determining the temperature of the radiator plate, simulating the temperature “inside of the spacecraft.” Once the setpoint was reached a thermistor on the surface of the back plate facing the cold plate was used to read the temperature of the thermal louvers and the temperature was recorded for each 1U thermal louver assembly. The resulting difference between open and closed louvers inside of a controlled environment with the same internal spacecraft temperature gave a difference in power dissipation to compare to the calculated values.

Table 1: Differences Between Open and Closed Louvers

Chamber Temperature (°C)	Heater Setpoint (°C)	Avg ΔT Open vs Closed Louvers (°C)	Power Dissipation Difference (W)
22.0	60.0	13.5	0.6
-20.0	60.0	11.2	0.5
-20.0	70.0	20.2	0.9

1U Heat Dissipation Testing Results

The results of this testing indicated that the calculated value of dissipated power was, as expected, higher than the actual dissipated power for a 1U thermal louver

assembly. Calculations assumed perfect conditions as well as components perfectly coupled to the back plate surface instead of radiative heating. However, these dissipation values and temperature changes were still significant amounts for a CubeSat.

1U Flap Opening Thermal Vacuum Testing Setup

The second round of thermal vacuum testing was initially going to be performed with the same doghouse setup, with a radiative plate and flaps facing the cold plate. However, this setup was not appropriate to use because a different chamber was selected for this test, and the new chamber had a vertical cold plate instead of a horizontal one and different electrical feed-throughs. It was necessary to switch chambers because the chamber for this test required a viewing port through which the louvers could be filmed opening and closing. There was not time to redesign the setup for the new chamber. Instead, the back plates were directly mounted to the cold plate itself, with a sheet of eGraf in between for better thermal conductivity.

Thermal vacuum testing was performed to gauge the degree of opening for thermal louvers in temperatures ranging from -20°C to 85°C over several cycles. Photos were taken every 10 seconds during selected representative cycles, and before and after photos were taken for every cycle.

1U Flap Opening Thermal Vacuum Testing Results

Results showed that the flaps on the 1U test assembly opened an average maximum of 44.6 degrees from 20°C to 85°C , and an absolute maximum of 70 degrees for the row with the highest angular displacement. These results were shown to be repeatable across cycles, just as in the life testing. There were two springs, one on each test plate, which caught against the front plates and were inoperable. These rows were discounted in the results.

The louver flaps showed predictable movement across the entire range from -20°C to 85°C , and were tuned to be even with the front plates at room temperature.

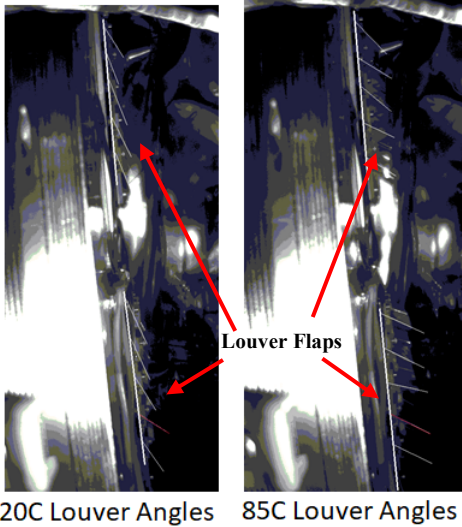


Figure 7: Louver Angles of Flap Opening Thermal Vacuum Test

FLIGHT DEMONSTRATION UNIT

The flight demonstration unit consisted of a single flap and bimetal spring, with a truncated front plate and back plate to fit the small space available within the Dellinger spacecraft. Because the unit was proposed as a payload after the scientific payloads and other subsystems were already in place, there was limited available space for an additional experiment. The unit was mounted inside of the spacecraft, which meant that it did not perform as an actual cooling technology for this particular spacecraft. It opened and closed due to a heater attached to its back plate. However, it did perform inside of the spacecraft in the way expected, repeatedly opening and closing and proving that the technology will work in a space environment. This flight pushed the technology to a Technology Readiness Level of 7.

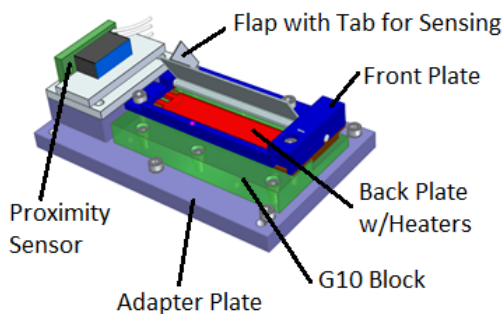


Figure 8: Thermal Louver Experiment on Dellinger

Flight Demonstration Unit Assembly

The flight demonstration unit consisted of several parts. The first was the unit itself, a single flap on a rod with a bimetal spring attaching it to the truncated back plate.

Holding the rod in place and covering the bimetal spring was a Ti64 metal front plate, with rod slots lubricated with Braycote for ease of movement.

In addition to the unit itself, a G10 block was machined into a mounting interface plate to thermally isolate the thermal louver unit from the baseplate of Dellinger.

The G10 block was then mounted to an aluminum adapter plate which held the G10 assembly as well as an infrared beam proximity sensor. The sensor was epoxied to the metal adaptor plate for the purpose of recording the opening or closing of the louver flap past a 30° angle. An aluminum shim was epoxied at a right angle to the flap for the purpose of reflecting the sensor's beam and providing feedback when the flap was above a 30° angle.

Two small Kapton heaters were epoxied with Stycast to the front and back of the truncated back plate of the louvers to heat the back plate and activate the bimetallic spring.

In addition, two thermistors were placed on the unit, one epoxied with Stycast on one of the heaters and one epoxied to the back plate right next to the bimetallic spring. These recorded temperatures during heating.

FLIGHT DEMONSTRATION UNIT TESTING

Flight Demonstration Unit Vibration Testing

The flight demonstration unit aboard the Dellinger spacecraft underwent qualification vibration testing per the GEVS-9000 standards. The unit survived and functioned properly after sine burst and random vibration testing. The flap was unconstrained during this test, which initially caused some visible damage to the Z93 white paint which had been deposited onto the back plate. However, lengthening the flap so that it vibrated against the front plate instead of the back plate solved this problem. The vibration testing was performed again with the flap overlapping the front plate and there were no issues in inspection or performance of the flight demonstration unit. The unit underwent workmanship vibration as a part of the spacecraft level vibration testing and there were no issues reported.

Flight Demonstration Unit Thermal Vacuum Testing

Flight qualification thermal vacuum testing was performed on the flight demo unit as a part of the Dellinger spacecraft level thermal vacuum testing. The flight demo unit functioned as expected during the spacecraft thermal vacuum test. In addition to the flight demo unit spacecraft level testing, independent thermal vacuum testing was performed on a 1U system of

thermal louvers to investigate spring performance as incorporated in the entire 1U thermal louver assembly.

FLIGHT DATA

Flight Details

The Dellingr spacecraft launched in 2017 and spent several months in space before the first run of the thermal louver experiment. The thermal louver experiment was considered low priority, with the heaters and sensor running only when commanded. There have been two data downlinks of the thermal louver experiment so far in the flight, with more anticipated to show any degradation or lack thereof in the flap opening over time.

Flight Data Analysis

The data from the thermistors and sensor showed that the louvers worked as expected. In the graph below the blue dashed line shows the status of the sensor. A “low” signal means that the infrared beam of the sensor was unblocked, with a louver flap angle less than 30°. A “high” signal (at 100 in this graph) means that the signal was blocked, with the flap at or over a 30° angle. The corresponding temperatures from the temperature sensors are shown in gray and orange. As expected, the heater temperature was higher, but both followed the same temperature curve as the flap opened. The flap took approximately five minutes to go from a fully closed position to a 30° angle of opening. Once the flap was open the heater turned off and the two temperature sensors read a decreasing temperature. In the experiment run on August 29th, 2018 the louver flaps reached a 30° angle at a 59.01°C spring case temperature and a 73.50°C heater temperature.

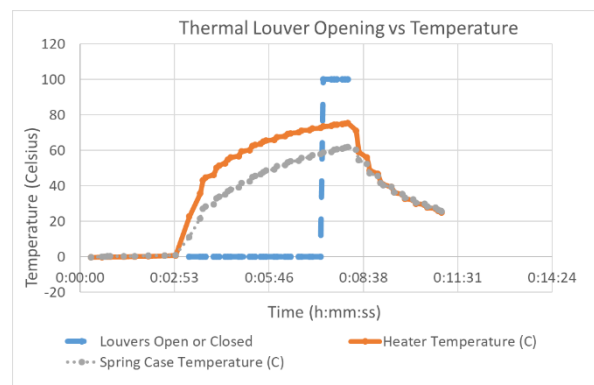


Figure 9: Thermal Louver in Flight 8/29/18

A second experimental run took place on August 31st, 2018 and the results were filtered in the same way as the first experiment. The results showed that the flaps opened consistently under similar temperature conditions while on orbit. For the second run the louver flaps took approximately five minutes to reach a 30°

angle. The flaps reached the 30° angle at a 57.88°C spring case temperature and a 72.58°C heater temperature.

Flight Data Conclusions

Both sets of data indicate that the CubeSat thermal louvers opened and closed successfully and repeatedly after several months on orbit. This qualifies as testing a prototype in a space environment, thus bumping the Technology Readiness Level of the CubeSat thermal louvers to a TRL 7. Further on-orbit experiment runs will determine how long the thermal louvers are proven to operate successfully in low Earth orbit.

CONCLUSIONS

The CubeSat thermal louvers were shown to operate successfully under a variety of conditions. The bimetallic springs which move the louver flaps showed no performance degradation after a life test of over 12,900 cycles. Louver flaps moved reliably after GEVS level vibration, during acceptance level thermal vacuum testing, and in a space environment. The testing done on 1U fully open vs fully closed louvers in a CubeSat-like operating environment showed a significant difference in power dissipation of 0.5W to 0.9W, depending on the internal and ambient temperatures. In addition, an experiment aboard the Dellingr spacecraft showed the louver’s mechanical resilience in space. Overall the CubeSat thermal louvers are proven to operate as a way to passively control the temperature of a radiating or conducting component inside of an isolated system.

This technology has applications in CubeSats and SmallSats carrying payloads which are sensitive to extreme temperature fluctuations. For example, louvers could help control the temperature of an instrument which is calibrated to work within a range of temperatures or a temperature sensitive component located close to a subsystem which occasionally reaches high temperatures. CubeSats are becoming more advanced, with subsystems such as propulsion and higher-powered communication. Concurrent with the advancement in CubeSat bus components is the arrival of CubeSat sized scientific payloads- frequently delicate sensors and prototypes of larger proposed instruments. This CubeSat thermal louver technology is proposed as a passive component option which may assist in stabilizing the temperatures inside of a CubeSat or SmallSat and allow these types of missions to advance.

FUTURE WORK

Future work on the CubeSat thermal louvers mainly focuses on determining the effectiveness of the louvers in maintaining a thermal set point in varying thermal conditions, both internal and external. This will require

further thermal vacuum testing with a set of functional thermal louvers thermally isolated from the cold plate and the back of the louvers and the heaters enclosed in a mylar blanketing or similar material. This test would provide data on the actual heat dissipation that the louvers can provide, outside of best case tested scenarios such as those performed in the preliminary testing.

In addition, future work may include modification of the louver front plates and/or back plate to decrease spring cover height to 6.5mm and tighten the width of the louvers to fit inside of the keep out zones for CubeSat rails. This would allow the thermal louvers to be used in 1U to 3U rail-type deployers.

Acknowledgments

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