Self Deploying Nitinol LHP Radiator for Small Spacecraft

Alfred L. Phillips
Thermacore, Inc
780 Eden Rd. Lancaster PA 17601; 717.519.3137
a.l.phillips@thermacore.com

Jentung Ku
NASA Goddard Space Flight Center
Mailstop 545.0 Greenbelt MD 20771; 301.286.3130
Jentung.Ku-1@nasa.gov

ABSTRACT

The use of nitinol (shape memory alloy) tubing for an LHP condenser allows a passive, self deploying heat rejection radiator for small spacecraft. The tubing is “trained” to its deployed configuration, then compactly coiled for launch. When the payload is energized and the condenser heats up, the shape memory alloy changes phase and returns to its trained shape. This paper reports on a NASA sponsored SBIR Phase I program that established the feasibility of the concept. Nitinol tubing was made from available material which had a phase change temperature much higher than desired. It was trained to a simple deployed shape. Since the ends of the LHP condenser are constrained, there are a limited number of basic, possible coiling arrangements. Early experiments used a loop thermosyphon with water working fluid to provide condensing vapor to heat the tubing internally and actuate the shape change. The later experiments used an ammonia loop heat pipe to successfully demonstrate deployment that was actuated by the heat being rejected.

BACKGROUND - NITINOL

Nitinol is a near equi-atomic (49.0 to 50.7 at.% Ti) nickel-titanium intermetallic compound. Below the transformation temperature it is Martensite with a twinned monoclinic structure. Above the transformation temperature it is Austenite with a cubic B2 structure.

Austenite can change to the Martensite structure under stress, and will then be able to accommodate up to 8% strain by an unconventional de-twinning mechanism. When the stress is removed, it returns to austenite and its original shape. This is the property that enables the amazingly flexible eyeglass frames that spring back to shape. It also enables its widespread use in the medical field for stents and catheter guide wires.

When Austenite is cooled below the transition temperature it becomes Martensite. It this state it is very flexible, and readily deformed. When the deformed Martensite is heated above its transformation temperature, it changes back into Austenite, and also changes back into the shape to which it was “trained” in the austenitic phase. It can exert significant force during this transformation and this enables its use as an actuator to deploy panels in spacecraft

The transformation temperature can be adjusted within the range of -100°C to +100°C by varying the composition and processing history.

THE NITINOL TUBING

Long Lead Time

There are a very limited number of foundries that produce nitinol. Manipulating the Ni-Ti ratio in nitinol materials is painstaking. The lead time to obtain a melt of material with the desired transformation temperature was 24 weeks. This was totally unworkable within a 26 week Phase I SBIR program, so an on-hand material with a higher transformation temperature than we would have preferred, had to be used. The tubing made from this material was heat treated and processed to lower its transformation temperature as much as possible, but the high transition temperature made the experiments much more difficult than anticipated.

Joining

The literature and advice from suppliers both indicated that shape change material cannot be welded. (Actually it can be welded, but the welds do not survive the phase transition.) This necessitated that all connections be accomplished with compression fittings. All testing was done using off the shelf connectors.

Since the austenitic nitinol is easily deformed there was some concern about the use of these fittings. A slightly thicker wall was used to reduce the probability of problems from this source. The tubing used was 0.125" OD with 0.012" wall. Some of the first testing in the program showed that the joints were very sound and tested well into the 9 scale on helium leak check, the same standards used for welded joints.

Coiling

If the austenitic material is deformed beyond its 8% elastic limit, it will not fully return to its trained shape after transitioning to Martensite. Using the 0.125" tubing would allow coiling to a 2 inch diameter.

The condenser of a loop heat pipe will have both ends constrained when it deploys which limits the number of ways it can be coiled. Figure 1 shows a simple way to make a coil where its ends are constrained.

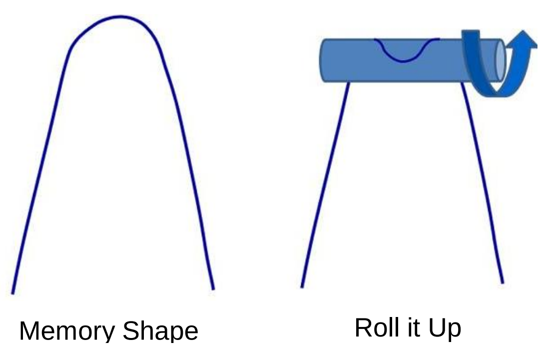

Figure 1 Forming the Constrained Coil

As formed, the memory shape (the left side of figure 1 is just a schematic representation) had a 1 inch radius curve at the top, and the bottom ends were four inches apart. All the memory shape training was done by the tubing supplier, as were the initial coils. Figure 2 shows the first coil as received.

Figure 2 The First Nitinol Coil (Dia ~2 inch)

Compatibiliy

Previous work on the JIMO Mission examined nitinol as a heat pipe material. Nitinol water heat pipes have been on life test since then and performed well. Every chemical consideration says that nitinol should be compatible with ammonia, but just to be sure, some nitinol ammonia heat pipes were fabricated and put on life test. The test pipes were made from larger diameter, electropolished tubes, so lengths of the small diameter tubing were included inside the pipes to preclude any unexpected effects from its oxide coating.

DEPLOYMENT TESTING

Eight significant tests were conducted. For both safety reasons, and for ease of processing when changing loops, the initial testing was performed using a loop thermosyphon (LTS) with water as the working fluid. The definitive tests used an ammonia loop heat pipe (LHP).

Tests with the Initial LTS Configuration

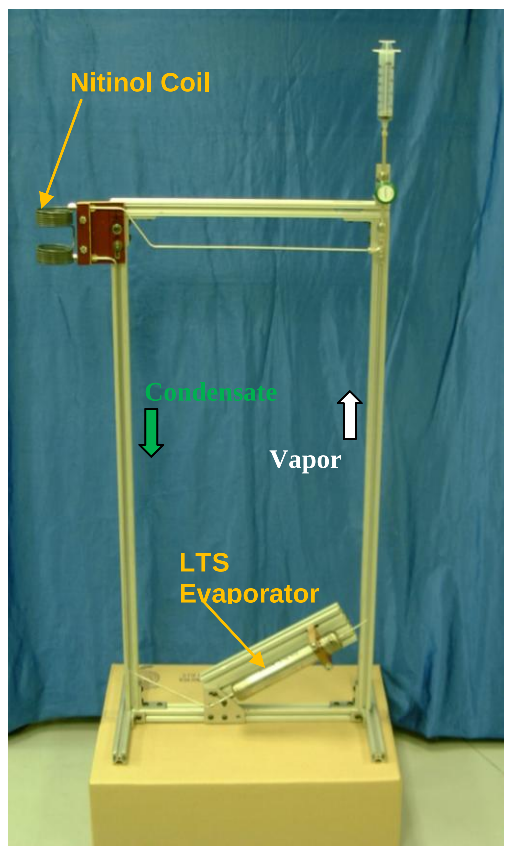

Figure 3 Initial LTS Test Configuration

Figure 3 shows the initial test configuration. The evaporator generated vapor that went up the right leg of the test loop, passed thru the coil and condensed, then returned to the condenser by gravity. The setup was based on the assumption that the tubing would uncoil by unrolling in the reverse of the process shown on the right side of Figure 1. As shown in Figure 4, the coil had other ideas.

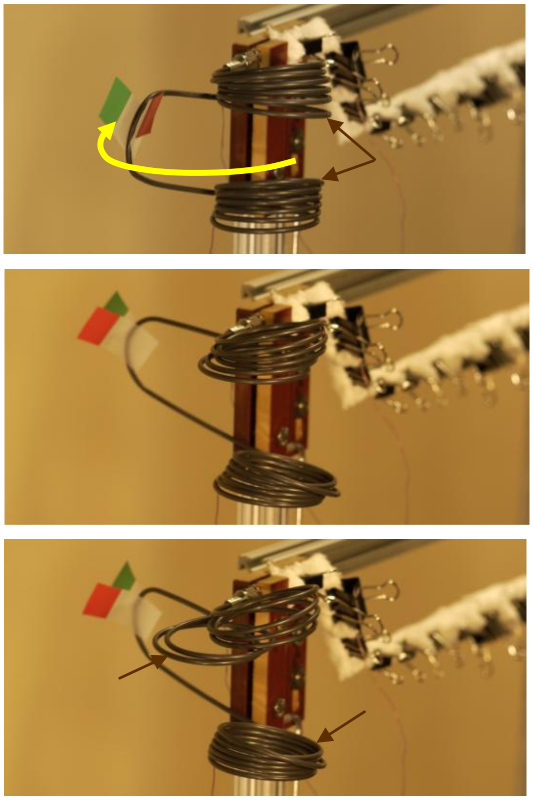

Figure 4 First Attempted Deployment

The top frame of Figure 4 shows that the first motion occurs on the center curve which has uncurled along the path shown by the yellow arrow. In hindsight, this is the least constrained portion of the coil so motion would begin here.

The middle panel shows the center curve running into the support structure. Note that the top part of the coil has expanded slightly while the bottom part of the coil has not. This indicates that the upper coil has reached its transition temperature and is trying to expand.

In the bottom panel, the only degree of freedom is the lower portion of the upper coil which is moving outward. The bottom coil is still not at its transition temperature and is not expanding.

Jacking the power input to the LTS to its maximum brought the lower coil to its transition temperature, but neither coil had anywhere to go. The final result is shown in Figure 5.

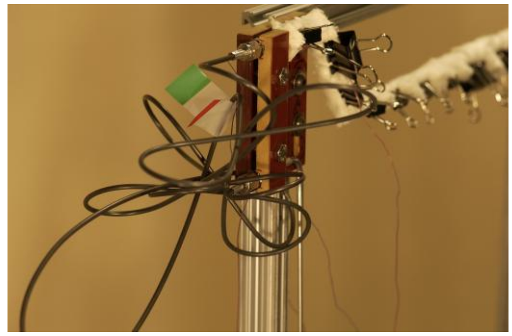

Figure 5 Final Shape from First Test

For subsequent tests, a gap was cut in the support so the initial swing of the center curve would not be impeded. (This would work as if the coil was wrapped around the satellite instead of being mounted on its surface.)

A second test was then conducted. In this test only the upper turn of the upper coil reached its transition temperature. This part of the loop tried to straighten, but pushed the rest of the coil into a configuration in which it couldn't move. Infrared photos showed that the first few inches were well above the transition temperature, the next few inches were right at the transition temperature, and the rest of the coil was essentially at room temperature.

The interpretation was that the vapor front from the LTS had reached the coil, but was not being maintained through it. Some analysis showed that at these temperatures, the water vapor was condensing before reaching the coil, and in the process was reaching its sonic limit. To increase the vapor density to preclude the sonic limit required a temperature well above the actuation temperature of the nitinol. The LTS was rebuilt to solve this problem.

TESTS WITH THE RECONFIGURED LTS

The coil used in the previous test was returned to its memory shape by heating it above its activation temperature using a torch. It was then rolled into a coil shape very similar to that in Figure 2. This produced our first successful deployment. Subsequent analysis of the data showed that although some movement began at 55°C, most of the deployment took place between 65° and 72°C. The test was repeated the next day using a virgin coil as received from the nitinol tubing vendor.

The deployment is shown in Figure 6 which is a series of stills taken from the mpg video documentation. The elapsed time for the stills is shown on each picture. The elapsed time for the sequence was 51 seconds.

In the last two pictures, the drooping of the deploying coil under gravity is apparent. While in the martensitic phase, the material is very flexible and will droop.

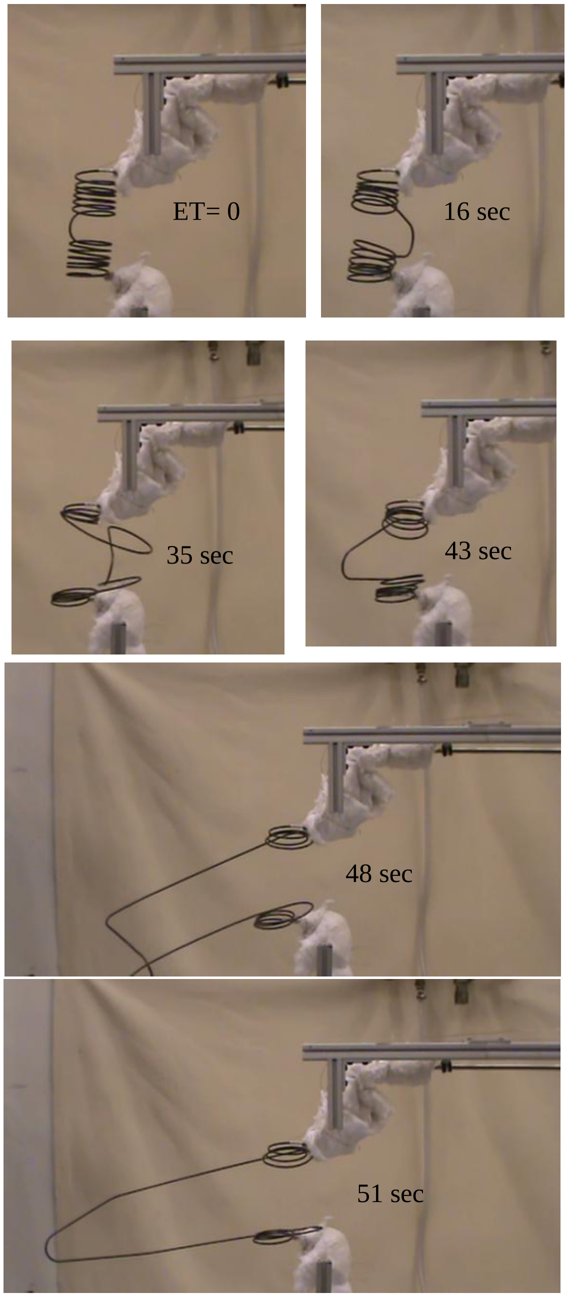

Figure 6 Deployment Sequence on 6/4/09

As it extended further, the drooping under gravity did cause the deploying coil to hang up on the lower support post and it had to be freed manually. Since gravity would not be an issue on a spacecraft, this aid was considered appropriate.

As the loop completed its transition to its austenitic phase, it becomes stronger and more rigid and eventually reached the full flag position shown in Figure 7.

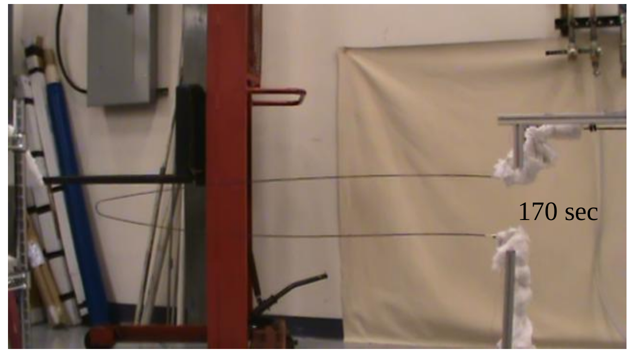

Figure 7 Final Deployment 6/4/09

This test was considered a complete success, but it had to be repeated using an ammonia loop heat pipe to really establish the feasibility of the self deploying radiator.

TESTS WITH AN AMMONIA LOOP HEAT PIPE

Figure 8 shows the lower part of the LHP while being processed and charged. An existing evaporator/CC was used. The evaporator is only an inch long. A heater block was later attached to the flat surface called out in the figure. The compensation chamber was undersized for this loop, but in a gravity-aided orientation in a lab environment this was not an issue.

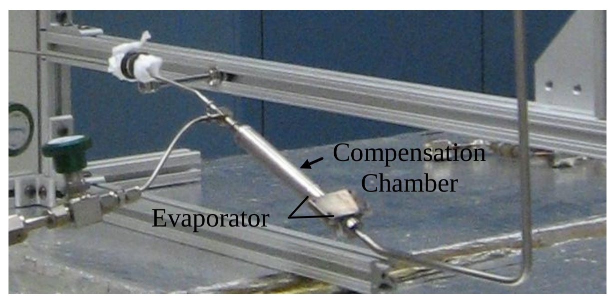

Figure 8 Evaporator, CC and Lower Loop

The First LHP Test 6/15/09

This test was mostly getting a feel for the LHP. Some slight motion of the coil was observed at 55°C. At maximum power, the temperature profile shown in Figure 9 was obtained across the nitinol coil. This did not produce any further deployment. The fall in temperature at the right side of the curve is a decrease in flow thru the coil caused by the LHP starting to deprime. The evaporator temperature continued to rise but it was now decoupled from the coil. In the interests of safety, the loop was shut down when the CC temperature surpassed 81°C.

The Second LHP Test 6/22/09

The small evaporator was clearly at its limit in the first test. Several approaches were considered, and an

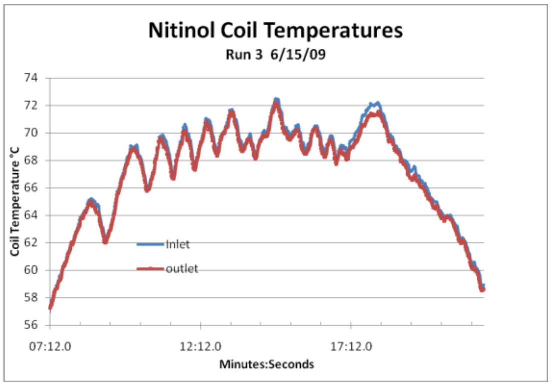

Figure 9 Peak Temperature Profile

approach employing a superheater was implemented. The superheater consisted of a heater tape around the vapor line just before it entered the nitinol coil. The idea was that the superheat could drive the vapor thru the coil, achieving stable operation at a temperature above the nitinol transition. A water cooled condenser downstream of the coil would remove the power added by the superheater so that the evaporator would not be overtaxed.

With the LHP running smoothly at 125 watts, the heater tape was powered to 20 watts. The temperature at the inlet to the nitinol coil went from 45.7°C to 58.°C. However the outlet of the nitinol coil increased only 2 K to 47.9°C. The superheat wasn't working, but the loop was stable. Power to the evaporator was increased in steps to the maximum available which is 195 watts. Superheat was reduced as was the flow rate of the water to the downstream condenser.

As the water flow was reduced, the temperature thru the coil began to rise. With the water essentially off, the loop could not reject the power that was being put into it, and began a ramp-up in temperature, but without depriming. The nitinol coil went to full deployment over a 12 minute period.

The uneven heating from the superheat experiment caused a skewing of the coil as it deployed. The experiment did provide a strategy that would allow us to reach full deployment temperature with the limited capacity evaporator. It was now possible to perform the definitive LHP deployment.

THE DEFINITIVE LHP DEPLOYMENT TEST

New Configuration

Instead of the inverted V memory shape shown in figure 1, the new configuration started with an inverted U shape that was wide at the top and narrow at the bottom. When rolled, this memory shape produced a coil that had the lines feeding from the center, and that had the curved return end spanning the two coil halves rather that nesting between them. The memory shape was re-trained by the tubing vendor, and was coiled by the PI.

Instead of having the coil just surrounding a piece of the test frame, it was wrapped around a 5 inch box that represents a CubeSat. The coil in the test configuration is shown in Figure 10.

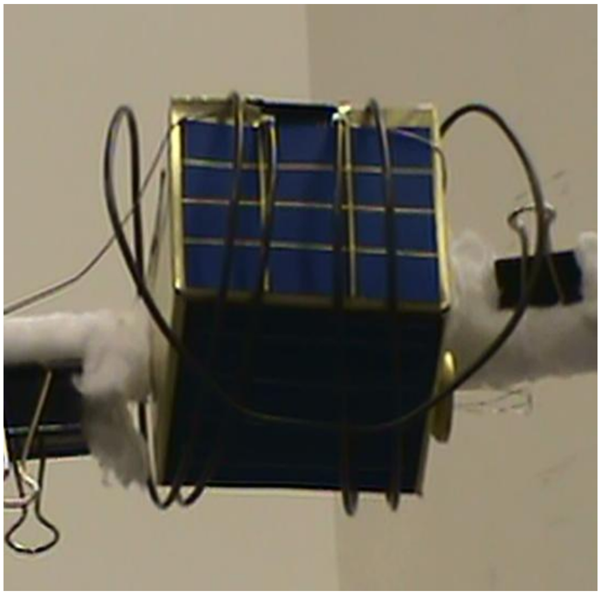

Figure 10 New coil configuration on "CubeSat".

The Deployment Sequence

The deployment is shown in Figure 11 which is a series of stills taken from the mpg video documentation. The elapsed time for the stills is shown on each picture. The first picture of the series, with ET= 0, is Figure 10. The numbers in parentheses are sequence number which provides a reference for the temperature versus time data presented as figure 12.

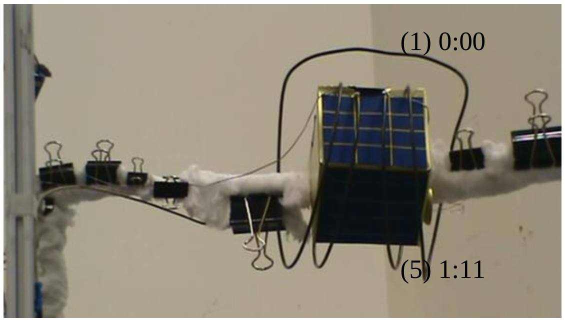

Figure 11.1 Still 5 of Deployment

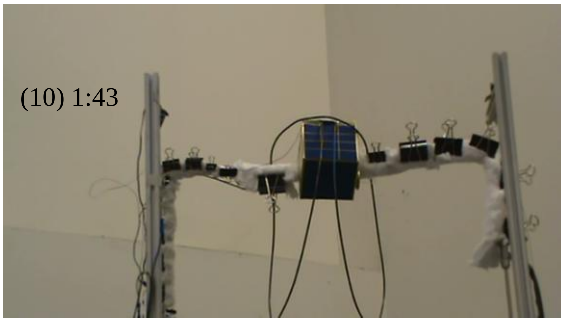

Figure 11.2 Still 10 of Deployment

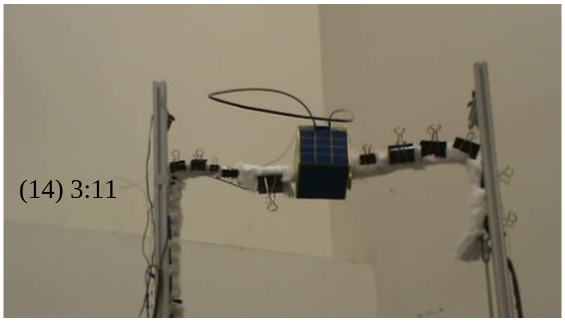

Figure 11.3 Still 14 of Deployment

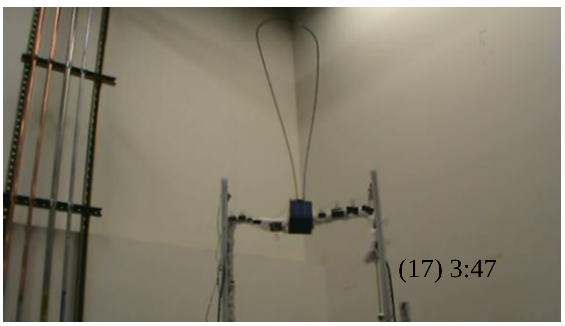

Figure 11.4 Still 17 of Deployment

Temperature History of Deployment

The deployment was initiated after a period of stable operation at maximum power of 197 watts. This produced a temperature near 53°C across the coil as shown on the left of the curve in Figure 12. At the beginning of the sequence, the cooling water flow to the condenser was cut off. Still #1 was taken at this time and is shown as Figure 10. The LHP then began a temperature ramp that reached 75°C at the time full deployment was achieved as shown in Figure 11.4. At this point coolant flow was restored and shortly after the loop was shut down.

One last piece of data was taken. When the temperature in the coil reached 49°C, the deployed radiator sagged under gravity.

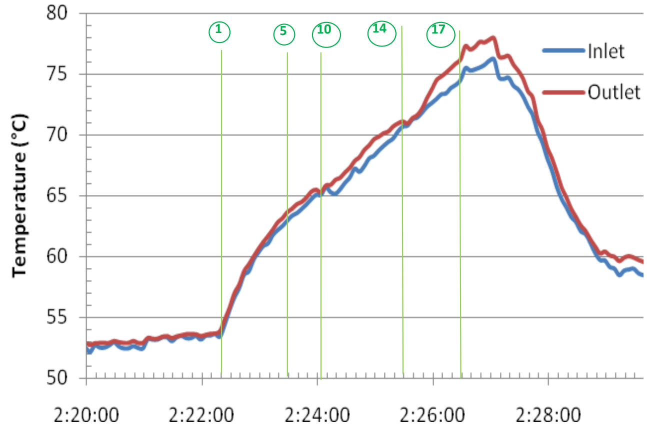

Figure 12 Temperature History Detail

CONCLUSION

The Phase 1 definitely demonstrated that a nitinol LHP radiator can be deployed by the heat being rejected.

While there the concept is nowhere near ready for flight, it will hopefully move into a Phase II where application details can be tied down. Anyone with an application that might benefit from the self deploying heat rejection radiator is urged to contact the authors to become the poster child application for the Phase II work.

Acknowledgments

The PI wishes to acknowledge the contributions of Bill Hochella for sharing his expertise on shape memory materials, and to Carlos Pimental whose hands-on skills made the concept a metallurgical reality. Both men work for Johnson Matthey although at opposite ends of the country, and without their help this demonstration would not have succeeded.

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