NASA's Jet Propulsion Laboratory
Pasadena, California 91109-8099

Technical Support Package

Temperature-Controlled Clamping and Releasing Mechanism

NASA Tech Briefs
NPO-40541

National Aeronautics and
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Technical Support Package

for

TEMPERATURE-CONTROLLED CLAMPING AND RELEASING MECHANISM

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An Autonomous Passive Optics Bench Release/Reclamp Device Using Shaped Memory Alloys

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ABSTRACT

The Tropospheric Emission Spectrometer (TES) is an instrument payload that will fly on the Aura spacecraft as part of the Earth Orbiting Satellite (EOS) program to study and measure global ozone distribution. This paper describes the novel approach using Shaped Memory Alloys (SMAs) to relieve stresses in the 100 kg TES optical bench after launch. The SMA passively releases the non-kinematically-mounted optical bench when cooled to its operating temperature of 180K and automatically reclamps the bench to regain full bolt preload when warm. This allows the bench to be unstressed during operation, safely survive launch loads and negates the need for manual intervention at the joint interface after every thermal test cycle. A full series of qualification tests were performed to ensure bolt preloads were regained at warm temperatures and full release occurred at cold temperatures.

1. INTRODUCTION

The Tropospheric Emission Spectrometer (TES) is an instrument flown on the Aura spacecraft, a part of NASA's Earth Observing System program, to measure state and composition of the Earth's troposphere (the layer of atmosphere extending from Earth's surface to 16 km in altitude.) While the instrument can detect and measure many components of the troposphere, one of its main purposes is to study ozone. This instrument will operate for 5 years to provide important data on where the ozone in the troposphere comes from and how it interacts with other chemicals in the atmosphere.

The TES instrument consists of a rectangular cyanate-ester composite optics bench mounted to a cyanate-ester composite main structure, or frame. The 100 kg optics bench contains the majority of the optical elements, including the KBr (potassium bromide) beamsplitter, retro-reflectors, corner mirrors, translator mechanism, detectors, and laser metrology. The optics bench is cooled to 177K during nominal operations on-orbit. Because of the complexity of the optical system, many test runs in a vacuum chamber to 177K were required to align the optics bench as a stand-alone component before it was installed in the main instrument structure frame. To save time, a simple piece of Mechanical Ground Support Equipment (MGSE) was used to hold the optics bench during the alignment thermal runs rather than install the optics bench into the flight main structure.

2. THE PROBLEM

Once the alignment of the optics bench was complete, it was installed in the main instrument structure frame and placed in a vacuum chamber for the instrument's system test validation program. The first test as a complete instrument system showed the optical alignment had been significantly altered from the optical alignment runs. Already behind the original delivery schedule, a tiger team was formed to assess what had gone wrong.

It was discovered that during the previous optical alignment tests, the MGSE had mounted the TES optics bench on a kinematic, six degree of freedom (DOF), mount. Upon installation into the flight structure, however, it was discovered the flight mount was over-constrained to 18 DOF. There were seven struts from the main instrument structure frame leading to the three optics bench mounting pads; the struts were rigid and had no flexures or other means to eliminate bending moments from being transferred into the optics bench once it was torqued down. (The seven struts were used to increase the natural frequency of the instrument above the required 50 Hz). It was concluded that the over-constrained mount imposed bending moments into the optics structure and caused its misalignment.

With the project already behind its delivery schedule, the prospect of re-aligning the optics bench in the main structure would take more than ten months because the optics bench would need to be removed from the main structure in order to make any alignment adjustments after each thermal-vac run. The bench would then have to be reinstalled in the primary structure and then put back into the vacuum chamber. If this option were exercised the instrument would most likely have missed its flight opportunity on the Aura spacecraft.

A different approach was needed.

3. CONSTRAINTS

The optics bench was mounted to the main structure struts at three points: pads on the tripod and each of two bipods. The tripod mount pad consisted of a pin joint (with 3 DOF) and used a ¼" bolt. One bipod had a slotted pin (2 DOF) and also had a ¼" bolt. The remaining bipod had an oversize hole and relied on friction from bolt preload to eliminate slippage during launch vibrations (1 DOF), however, this location used a 7/16" bolt because of the greater clamp force needed for the friction joint to prevent slippage during launch loading conditions.

Although there were only three mounting pads and the pins provided a kinematic (6 DOF) support, any misalignment of the pad surfaces between the optics bench pads and the strut pads on the main structure meant that bending moments were transferred across the pads into the optics bench. This most likely caused the bench to warp once the mounting bolts were torqued down. Clearly, if the bolt torques could be released, the optics bench would be held in a kinematic (6 DOF) manner, with the use of the existing pins.

A test was done on the flight instrument in the vacuum chamber where the optics bench bolt torques were removed, i.e., loosened. The instrument performed as it did during its last stand-alone optics-bench alignment test, i.e., it was aligned properly and performed to specification.

The team realized that the TES instrument could be delivered on time to the Aura spacecraft if a bolt release device could be implemented and qualified in less than three months. The device would have to:

1) Hold the bolt preload to above a defined, minimum level for launch and system-level vibration testing, both at JPL and on the Aura spacecraft. It was expected that the device would need to go through 4 vibration cycles, including launch, so a factor of safety was imposed that the flight-qualified device would need to <u>reclamp</u> properly after at least 16 cycles to still retain the proper bolt preload for launch conditions. This was most crucial at the 7/16" bolt joint where friction was required.

2) Release the optics bench bolt torques completely when the instrument entered its operational thermal regime at 177K. This could only be assured if the device provided an open "gap," then belleville springs could provide a known force to gently register the optical bench on the desired main structure surfaces.

3) Because the TES mission life was 5 years, there would be periodic decontamination events on orbit where the optics bench would be warmed to room temperature. At the same time that the optics bench misalignment was discovered, the potassium-bromide beamsplitter developed an anomaly where it would "walk", or constantly shift position as a result of the loss of preload on its RTV mounting pads. The workaround for this anomaly was to warm the optics bench to room temperature to "reset" the KBr to its original (aligned) orientation every 5 weeks. At the worst case, these thermal cycles were expected to happen 50 times over the 5 year period; so a constraint was imposed on the bolt release device that it had to be able to <u>release</u> fully after 200 cycles, or a factor of safety of 4 times the expected number of on-orbit cycles.

4) Fit within the mechanical confines of the optics bench and main structure and have minimum electrical and power interfaces, preferably none. There were 2 sizes of fasteners used at the 3 bench mounting locations: a ¼" bolt at the tripod mount (this mount had the pin); a ¼" bolt at the bipod mount containing the slotted pin, and the 7/16" bolt at the oversize hole bipod mount that required friction to prevent slip during launch vibration loads.

4. SOLUTION

The Shaped Memory Alloy (SMA) was an ideal candidate for the bolt release device because it would not require any special electronics, commands, or complex interfaces to the existing instrument or spacecraft. An SMA alloy was available that would provide the required clamping force when warm, release when the optics bench was cooled to 177K, and then regain most of its clamping force every time it was warmed to +22 C.

4.1. Theory

Shape Memory Alloys (SMAs) are metals that change crystalline structure at predetermined temperature ranges – the actual temperature range depends on the alloy of the SMA. Most commonly, the hotter state, called austenite, has a rectilinear relationship between atoms. The cooler state, called martensite, has a rhomboidal or slumped relationship between atoms (see Figure 1). The difference in crystalline structure contributes to significant differences in material properties. In particular, the cooler martensitic material has a lower yield strength than the hotter austenitic material. If SMA is shaped when heated, then cooled below its martensitic transformation temperature, then deformed (within an acceptable strain level) while cool; then, when reheated, the SMA will proceed into austenite, its high-temperature phase, and return to its original shape. A way to think of the shape change phenomenon is that the cooled martensite can be loaded so that deformation occurs to align all the rhomboidal crystals one direction. On heating, the rectilinear relationship is re-established and the strain can be completely recovered. If the deformation is greater than the amount needed to push all the rhomboids in the same direction, then the part will not return all the way to its original shape. If the amount of strain is limited, then the shape recovery is very repeatable and reliable. The strain limit for repeatable performance is dependent on the alloy of the SMA, but is usually around 5%.

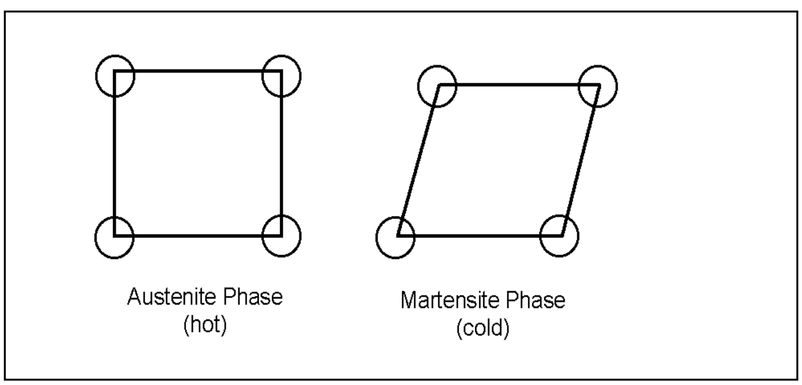

Figure 1. SMA molecules change shape when cooled and can provide work when heated to regain induced strain.

SMA can also be trained to exhibit two-way phenomenon. The training involves cycling the material between an original and deformed shape while heating and cooling the part. This requires loading the part when cool to strain it into its cool, deformed shape, heating to recover the original shape, then repeating the process. After many cycles, when the part is heated, it returns to the original shape, and when cooled it assumes the deformed shape. The physics behind this is hypothesized to be that the molecules induce microstrain on each other as they assume their original rectilinear austenitic shape. This micro strain causes the molecules to slump in the desired direction when the material is cooled to the martensitic state thus creating the desired shape deformation. The strain limit for two-way SMA performance is smaller than that required for one-way performance for repeatable, reliable two-way SMA performance – usually best limited to less than 2% depending on alloy.

SMA does not undergo phase transformations at a single temperature. The transformation occurs over a temperature range for each phase as shown in Figure 2 below. M_s marks the start temperature of the transformation to the martensitic phase. The transformation finishes at M_f. As heating takes place the austenitic phase transformation begins at its start temperature, A_s, and finishes transformation at A_f where it has fully recovered its original shape. Note also that there is a significant hysteresis effect between cooling and warming performance.

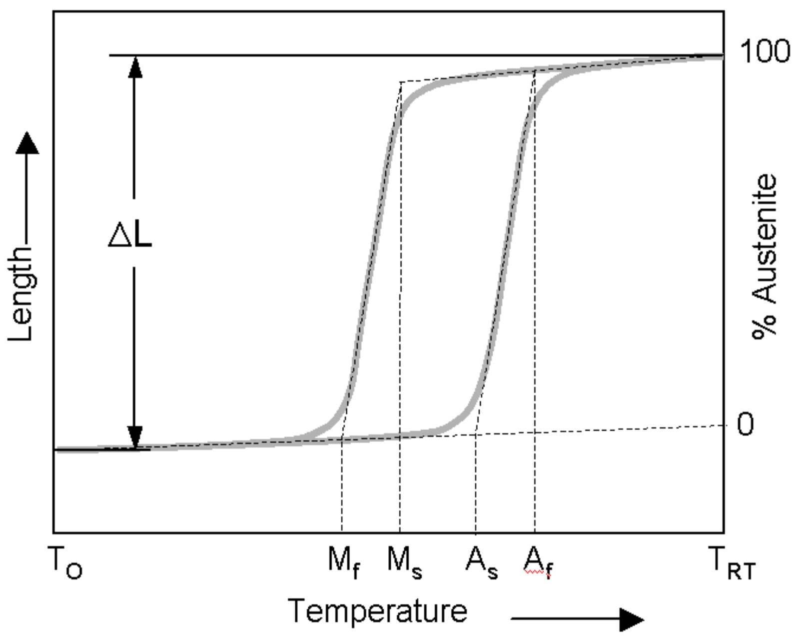

Figure 2. Length v. temperature of SMA including hysteretic properties

When the SMA returns to its original shape due to a temperature change, it can perform work. The force that can be produced depends on the alloy used, and the stress that is generated. As long as the stresses are kept low enough to prevent strain above the limits mentioned above, the part can perform repeatable work reliably. In a situation where the part is loaded, the temperature must be hotter than in an unloaded situation to fully reach the Austenitic phase – more energy is required to return the molecules to the rectilinear state. The relationship between load and temperature increase depends on the alloy and can be provided by the vendor.

4.2 Analysis:

In this application, a SMA washer was designed that would shrink enough to unclamp when the system changed from room temperature (20C) to about –90C. The materials being clamped were the invar part, stainless steel washers, fully clamped Belleville washers and the SMA washer. The Bellville washers pressed the optical bench against the reference surface of the mounts when the joint was released. The clamping bolt was stainless steel. Because the thermal coefficient of expansion (CTE) of the invar is much lower than the CTE of the steel, without SMA in the system the joint would tighten as the system cooled. The length of the SMA had to compensate for this and for the stretch and compression of the materials due to torquing the bolt. To complicate matters further, the CTE of the SMA changes as the material changes state. In addition, as the system warmed up after testing on the ground, the SMA had to reload the bolt enough to constrain the system during launch.

The equations for thermal changes in length caused by CTE was:

$\Delta L_T = \Delta T * L * CTE$

where

ΔT designates change in temperature from room temperature
L designates room temperature length
CTE designates coefficient of thermal expansion for the temperature range

And also for the SMA, the equation for the thermal change in length caused by a change in state was:

ΔL_{SMA} = L* % state change = L * 0.015

The equations for flexibility of the material was:

Fl = L/(A*E)
where
Fl designates flexibility in units of force/length
L designates room temperature length
A designates cross-sectional area of the part
E designates Young's Modulus of the material

The length of the SMA part was chosen to create a gap at –90C using the equation:

Gap = -ΣFl(clamped)*P - Fl(bolt)*P- Σ ΔL_T (clamped) + ΔL_{SMA} + ΔL_T (bolt)

where
ΣFl(clamped) designates the sum of flexibility of all clamped materials
P designates the preload of the bolt
Fl(bolt) designates the flexibility of the bolt
Σ ΔL_T (clamped) designates the sum of thermal length change of all clamped materials
ΔL_T (bolt) designates the thermal length change of the bolt

The area of the SMA part was calculated so that the stress capability of the part would provide adequate preload to the bolt for surviving launch loads with the allowed margins. It was important to determine that the stress buildup in the SMA did not exceed the stress limits for repeatable and reliable gapping performance.

Because this application had never been tried prior to this time, margin on the gap, the loads required, and the change of state effect were generous. This paid off when the system worked well through the first test. Because of the effect of the load on the SMA, the system did have to be heated above room temperature to fully load the bolt after the cryogenic testing on the ground.

4.3 Design

It was determined that a 5 cm (2 inch) stack of SMA alloy would be able to provide the requisite gapping with the desired release gap and reclamp force margins. The 7/16" bolt could fit within the optics bench, however, the two ¼" bolts needed to fit under the bench between the struts in the ¾" diameter counterbore in the strut fittings. After a preliminary analysis, it was discovered the ¼" bolt stretch calculations showed that the ¼" bolt stretched too much when it was torqued. This bolt stretch then prevented the 5 cm (2 inch) SMA stack from completely releasing the preload and giving a positive gap. Increasing the SMA stack to gain more release meant the bolt needed to be longer, which meant the bolt would stretch even more. This resulted in the same, minimal gap. This problem was solved by placing a stovepipe-hat load transfer piece under the head of a short bolt to transfer the load to the SMA. This reduced the bolt length and minimized its stretch while allowing the SMA to provide a positive gap margin when cooled. See Figure 4.

Because of the greater cross-sectional area of the bolt, the 7/16" bolt could be simply extended to include the full length of the SMA stack without causing excessive stretch. The SMA diameter was chosen to keep internal SMA stresses below the 30 ksi maximum working stress. This resulted in a 2.5 cm (1 inch) diameter SMA. Unfortunately, there was an offset in the bolt through-hole location in the machined invar pocket in the optics bench, and the SMA diameter would interfere with the wall of the pocket. The diameter of the SMA was shaved on one side to allow it to fit within the pocket. Stress calculations showed that the maximum working stress of the SMA (30 ksi) would be exceeded in this configuration because of the bending moment placed on the SMA when the bolt was torqued down. This was alleviated by making the SMA symmetrical, that is, shaving the diameter equally on both sides about the centerline. This eliminated the bending moment and reduced peak stress to the SMA allowable limits. Refer to Figure 3.

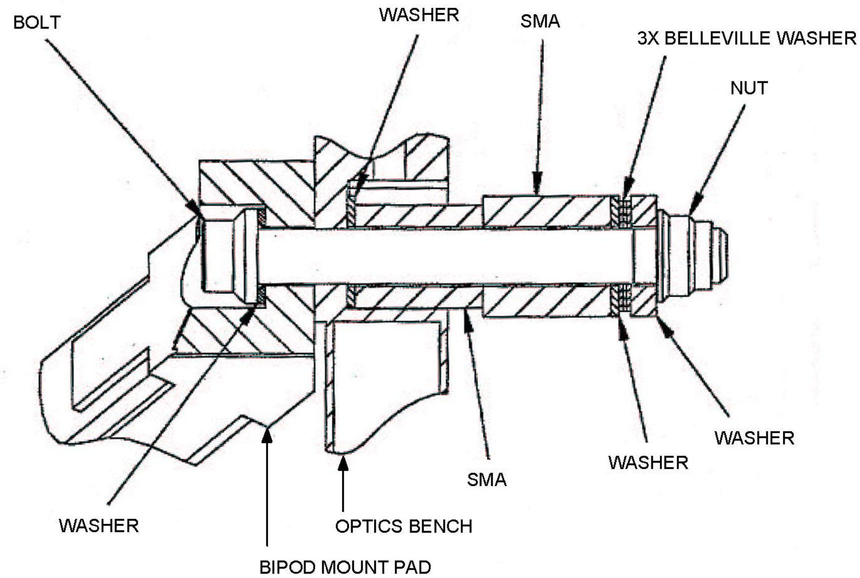

Figure 3: Cutaway of 7/16" bolt assembly showing SMA clearance problem with optics bench pocket.

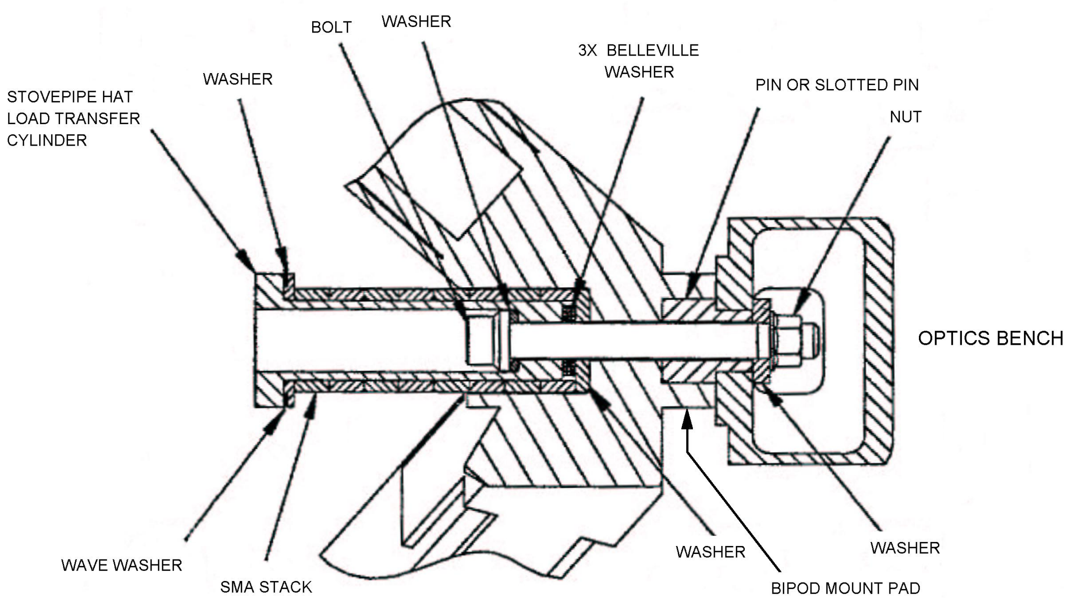

Figure 4: Cutaway of ¼" bolt assembly used at the bipod (slotted pin) and tripod (pinned) mounts. Note that eight sections of SMA were required to complete the 5 cm (2 inch) stackup because the wall thickness was so thin the material could only be "trained" in small lengths. Note also the "stovepipe hat" section used to transfer load to the SMA while minimizing the length of the ¼" bolt; this minimized bolt stretch and maximized the gap created at operational temperatures.

Each ¼” and 7/16” bolt assembly was provided with ~100 pound-force Bellville washer to provide a token clamp force between the optics bench and main structure frame when the SMA was cooled. This would prevent any motion of the optics bench with respect to the mounting frame in zero-g conditions on-orbit, even under worst-case spacecraft thruster activity.

Washers placed under the SMA were needed to eliminate any chamfers that would be required on the SMA material to clear the radii in the counterbores or other interfaces around the SMA. This eased the vendor’s task for “training” the SMA and eliminated a need to grind a precision chamfer on the SMA. This also maximized the contact surface area on the SMA to keep the maximum working stress below the 30 ksi limit. This was especially crucial on the ¼” SMA stack where the wall thickness of the SMA was not as high as desired because of the need to fit within the existing counterbore.

4.4 Testing/results

The testing program needed to validate two things: First, that preload was regained every time the SMA stack was warmed, and second, that positive gapping margin was created every time the SMA was cooled below 185K. The SMA vendor recommended that the SMA be warmed to +30 C or above to regain the full preload, however, the TES optics bench was only allowed to go to an upper limit of +22 C. This eight degree difference would not allow the SMA to regain its full preload, however, it was hoped that it would regain enough to meet the minimum preload requirements.

The test program was devised to validate the concept. A flight-like stack was made for each of the ¼” and 7/16” bolt assemblies and a test fixture was rigged in a vacuum chamber to run both simultaneously.

Both ¼” and 7/16” SMA bolt assemblies were tested for bolt preload retention after thermal cycling. The procedure used a point micrometer (accuracy to within .00015”) before and after the cycles to measure bolt elongation. This elongation was then used to determine the ultimate bolt stretch which directly corresponded to the preload in that fastener. A set number of thermal cycles (4x largest number of intended thermal cycles on the flight hardware) were completed with bolt stretch recorded. Any degradation of preload was then quantified. At the cold condition, an optical

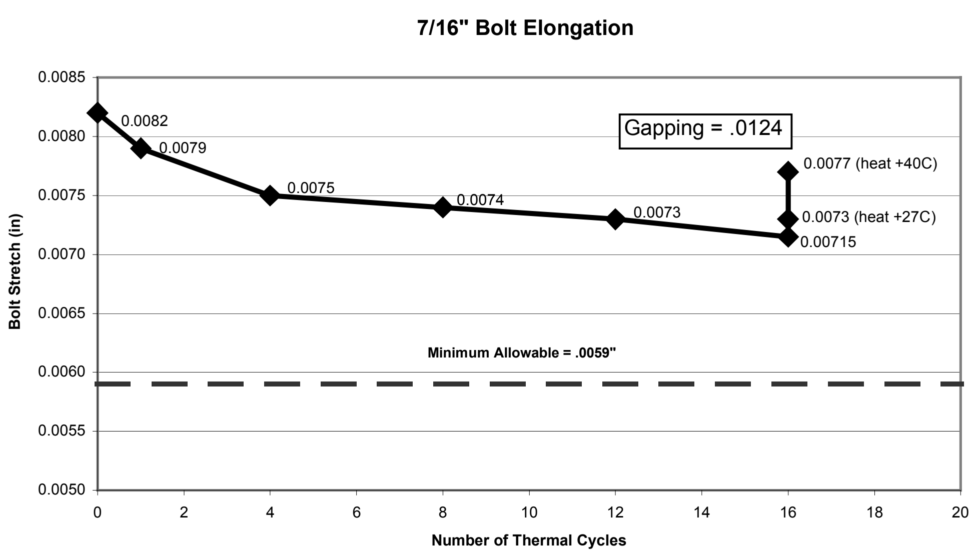

Figure 5: Shown is Bolt Stretch versus Number of Thermal Cycles for the 7/16” bolt during thermal cycling testing from 22°C to –88°C. A line for the minimum allowable elongation is also given. The final two data points show the effect of heating the SMA to +27°C and +40°C respectively. The gapping seen as a result of the SMA shrinkage can be found in the white box and was consistent throughout the test.

system recorded the SMA shrinkage. As long as the SMA shrinkage was larger than the bolt stretch, the preload of the system was removed as the design intended. Small gapping that may have occurred was removed with Belleville or wave washers (SMA shrinkage = Bolt stretch + Belleville/wave washer gap).

Figure 5 shows the bolt stretch as a function of the number of thermal cycles for the 7/16" SMA test assembly. The rate of preload loss is greatest after the first four cycles and slows considerably thereafter. One of the reasons why losses occurred was due to the SMA only reaching room temperature (22°C) instead of its full austenite state. (40°C) After 16 cycles the bolt elongation remained significantly greater than the minimum allowable bolt elongation needed for the TES flight qualification. The SMA shrank an additional 0.0124" more than the bolt stretched. The resulting gap was controlled with Belleville and wave washers.

Two additional measurements were made after 16 thermal cycles to test the effects of additional heating of the SMA to its full austenite state. A thermal oven was used to raise the temperature to ensure that equal and not excessive heating was seen throughout the SMA stack. The SMA was heated to 27°C, cooled to room temperature (22°C), and measured for bolt elongation. The same procedure was then used for a 40°C condition. As seen in Figure 1, much of the lost bolt elongation was regained thus validating this technique as a method to recover bolt preload if needed.

Bolt elongation for the ¼" assembly is shown in Figure 6. As seen in the 7/16" assembly, there was an asymptotic loss of elongation associated with thermal cycling. Some recovery was noticed on the third cycle, this is attributed to measurement uncertainty rather than actual elongation return. After the first cycle, the bolt elongation had decreased below the minimum level. A reheat process identical to the 7/16" SMA assembly was preformed which raised the elongation to an acceptable level after 16 cycles had been completed. In order to simplify the flight qualification procedure as well as to minimize risk, another 16 cycles were conducted starting at a higher initial elongation value. As predicted, the same curve but translated upward was produced. A gap between the SMA stack and the supporting hardware was removed with wave washers. A total of 0.009" and 0.008" of SMA additional shrinkage from the necessary bolt stretch was observed throughout the test.

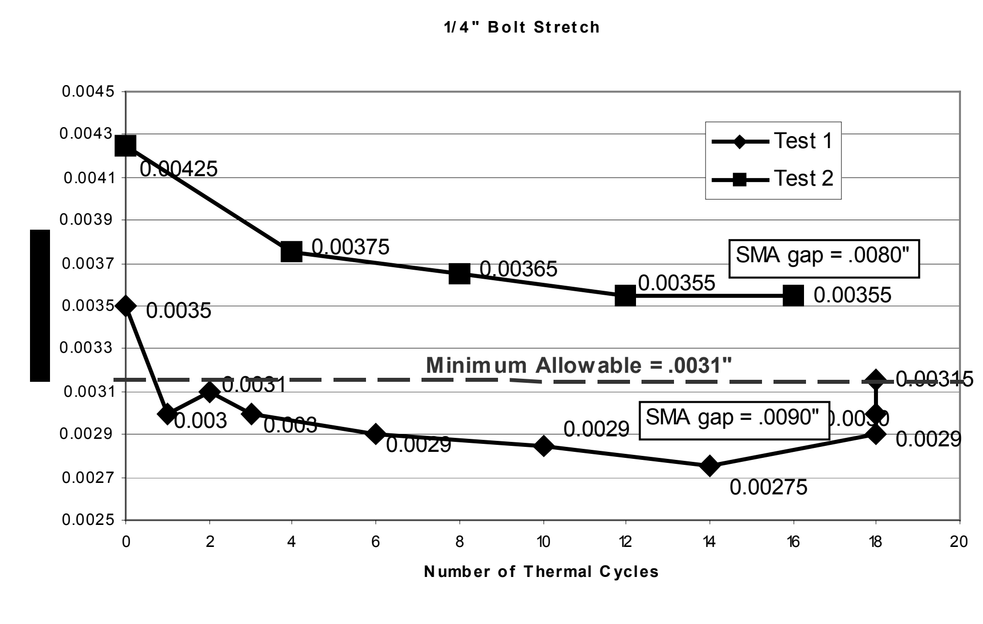

Figure 6: Shown is Bolt Stretch versus Number of Thermal Cycles for the 1/4" bolt during thermal cycling testing from 22°C to –68°C. A line for the minimum allowable elongation is also given. The final two data points show the effect of heating the SMA to +27°C and +40°C respectively. The gapping seen as a result of the SMA shrinkage can be found in the white box and was consistent throughout the tests.

5. CONCLUSIONS AND ACKNOWLEDGMENTS

5.1 Conclusions

Upon installation into the flight instrument, the passive release system enabled the TES optics bench to remain aligned and perform to the desired specification at every subsequent alignment test. The TES instrument was shipped in time to be installed on the Aura spacecraft.

After extensive testing, the SMA system proved to be a reliable, effective, and predictable solution for passive release. This technology is not only useful for maintaining optical alignments where stiff structures are needed for launch, but it can also be used in applications where post-launch thermal isolation is required in cryocooled areas of spacecraft or spaceborne instruments.

5.2 Acknowledgments

The authors wish to thank the staff at Intrinsic Devices, Inc. of San Francisco, California, for their unfailing support and rapid production of the SMA devices. Without their help and expertise the TES instrument could never have been delivered on time.