53410

A New and Innovative Use of the Thermal Knife and Kevlar Cord Components in a Restraint and Release System

Alphonso C. Stewart
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771, USA
(301) 286-5560 (work)
(301) 286-0241 (fax)
alphonso.c.stewart.1@gsfc.nasa.gov

Abstract

A Kevlar cord and two thermal knives are key components in the Solar Array Restraint and Release System (SARRS) on the Microwave Anisotropy Probe (MAP) spacecraft at NASA's Goddard Space Flight Center. The SARRS uses a 25-foot (7.62 m) length Kevlar cord that encircles the spacecraft and secures the solar panels in stowed configuration for launch. Once in orbit, one of two redundantly configured thermal knives severs the Kevlar cord and permits the panels to deploy. The purpose of this paper is to present the details of the design, development test results, and the various innovations that were created during the development of this novel use of the thermal knife and Kevlar cord.

MAP Spacecraft

The MAP mission is to measure the temperatures of the cosmic background radiation over the full sky. MAP was launched into low earth orbit by a Delta II 7425-10 rocket. After separation from the rocket, the solar arrays and sun shield deployed (Figure 1) prior to the spacecraft continuing to an orbit about the L2 Lagrange point.

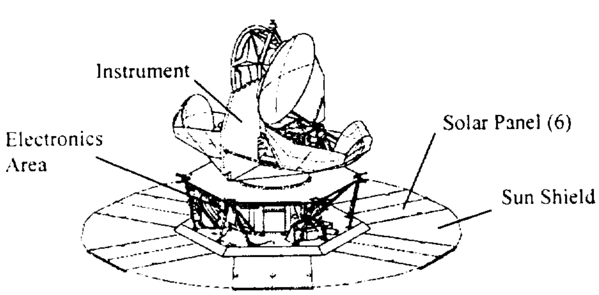

Figure 1: MAP Spacecraft in Deployed Configuration

MAP spacecraft design mass is 840 kg. It is 12 ft. (3.7m) tall, 9 ft. (2.7 m) in diameter stowed, and 12.6 ft. (5.1 m) diameter when deployed. The SARRS secures the solar array panels and portions of the sun shield in the stowed configuration as shown in Figure 2. The SARRS main requirements are as follows:

1. Secure the solar panels and sun shield in stowed configuration for ground transportation and launch
2. Consume less than 20 watts of power in 150 seconds per activation in releasing the solar panels on-orbit.
3. Generate low release shock and minimal risk of solar cell damage during deployment
4. Complete engineering development within project schedule

Trade studies of various restraint and release systems were investigated during the early development stages. The SARRS was the one design that met all of the restraint system requirements and will be presented in this paper.

Restraint and Release System Description

The MAP SARRS was designed to meet all requirements and address other issues such as actuator cost and delivery schedule, ability to test the flight component, access to restraint components during stowage, and minimal risk of potential solar cell damage during deployment actuation. The SARRS consists of twelve cable standoffs, one Kevlar cable assembly, and two thermal knives with mounts.

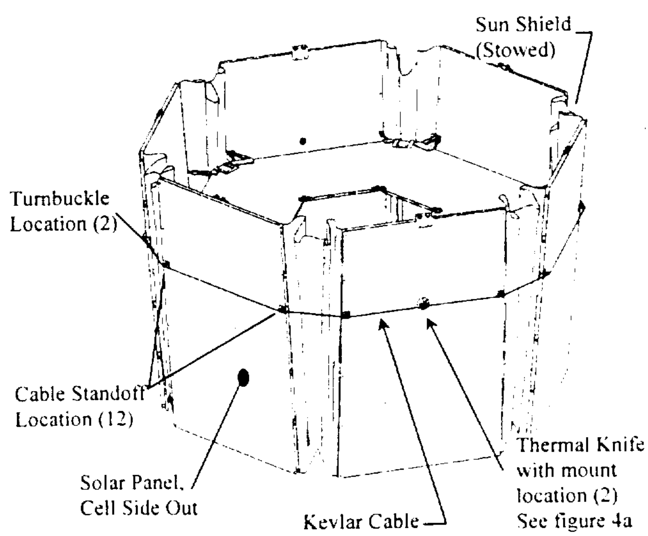

Figure 2: Stowed Configuration (Instrument not shown)

Two cable standoffs are positioned on the outer edge of each solar panel (Figure 3). The standoffs position the cable 1.3 inches (3.3 cm) above the solar cell and help secure the panels in the stowed configuration. The cable assembly is constructed of two Kevlar cord sections (150 in., 381 cm) that are joined by two titanium turnbuckles as shown in Figure 7. The turnbuckles are used to adjust the tension during cable installation.

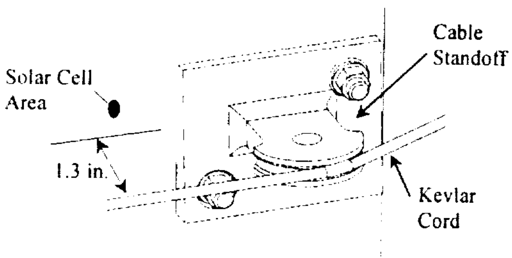

Figure 3: Cable Standoff with Kevlar Cord

There are two thermal knives in the SARRS. Each knife is held in its mount (Figure 4a) attached to one of two solar panels on opposite sides of the spacecraft. The cable standoffs and mounts are positioned such that the cable remains in contact with the thermal knife heater element until it is severed. The heater element is pressed towards the Kevlar cord by a spring within the thermal knife.

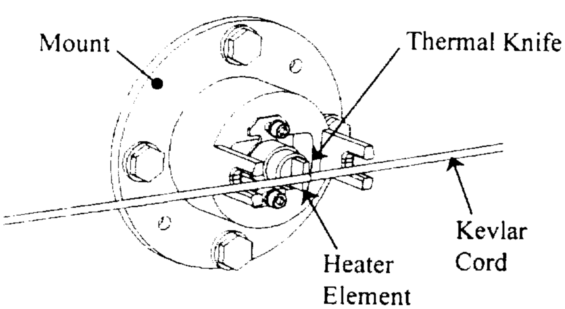

Figure 4a: Thermal Knife in Mount

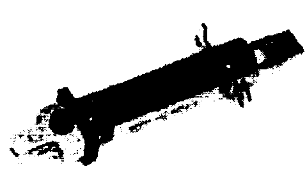

Figure 4b: Thermal Knife

To deploy, power is applied to either of the two knives that generates temperatures in excess of 1000 °C. The Kevlar cable tensile strength starts to degrade as the fibers break where the heater element makes contact. The degradation continues until the cord's strain energy suddenly breaks the remaining fibers and releases the panels.

Concept Analysis

Prior to building a prototype test unit, computer models were generated to investigate the cable release dynamics. The models were used to determine whether the panel geometry would allow the cable to travel free of the observatory. In addition, parametric models were used to determine which parameters, such as standoff-to-cable friction or cable tension, dominate cable behavior during release. The results indicated that cable tension is the primary factor in generating cable velocity in clearing the spacecraft.

Concept Development

The prototype test unit consisted of a wooden structure simulating the outer panel geometry, aluminum cable standoff simulator, restraint cable with a single turnbuckle, and a single thermal knife. See Figure 5.

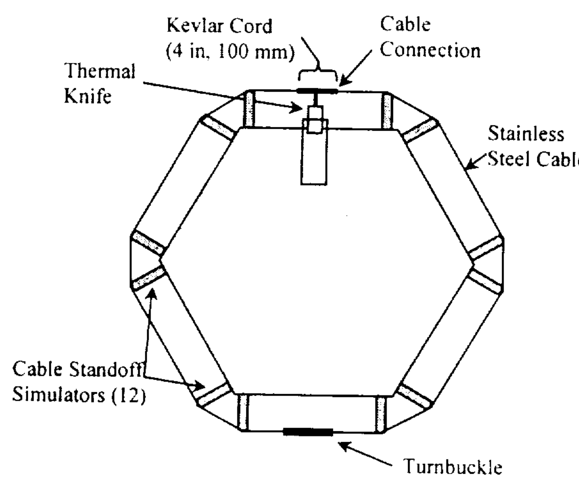

Figure 5: Top View, Prototype Testing Setup

The initial cable assembly was made of 0.09 in. (2.29 mm) diameter stainless steel cable with a 0.125 in. (3.175 mm) diameter Kevlar cord section of 4 in. (10.2 cm) in length at the thermal knife location. The stainless steel portion of the cable configuration was selected because of the relative low strain to tension load and experience with using all stainless steel cable in similar manner on previous spacecraft. Several cable release tests were performed to evaluate the cable dynamics. High-speed video results indicated the Kevlar-to-stainless steel cable connection areas would strike the cable standoff and possibly damage the solar cells in the flight design. The cable was reconfigured with a longer Kevlar cord section that placed the cable connections on the opposite side of the first two cable standoff simulators as shown in Figure 6.

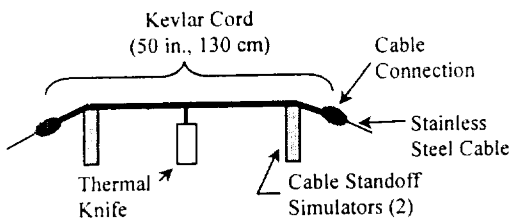

Figure 6: Extended Kevlar Section

Testing with a longer Kevlar section showed no signs of impact with standoffs, however, other concerns were raised. The frictional forces between the stainless steel cable and standoff were preventing the tension from being distributed evenly using a single turnbuckle. Secondly, the release shock within the cable momentarily drove the cable section opposite to the cutting towards the solar cell area. Any contact by the stainless steel cable or turnbuckle with the solar panels could cause solar cell damage. To minimize these concerns an all-Kevlar cable with a single stainless steel turnbuckle was constructed.

The initial testing of this design proved that an all Kevlar cable design was possible, however, the turnbuckle must still be relocated to mitigate possible solar cell damage. Additional concerns such as large strain and load relaxation would also be addressed during development.

Kevlar Cable Development

The all-Kevlar cable design requires a large strain (~12 in., ~300 mm) to achieve the proper tension. The Kevlar cord is constructed of woven Kevlar fibers that are at various angles with respect to tension load. When tension load is applied, the fibers try to align themselves in the load direction and extend the cable length. It was known that load cycling the Kevlar cable will increase its stiffness and would require a shorter turnbuckle travel to achieve the same load.

The turnbuckle was redesigned and relocated between the panels in two locations 180 degrees apart and 90 degrees away from the thermal knives. The new turnbuckle design was shorter and fit within the space of two standoffs on adjacent panels. In addition, the two-turnbuckle design provides a more even tension distribution around the spacecraft. Their location between the panels mitigates the potential for solar cell damage during cable release.

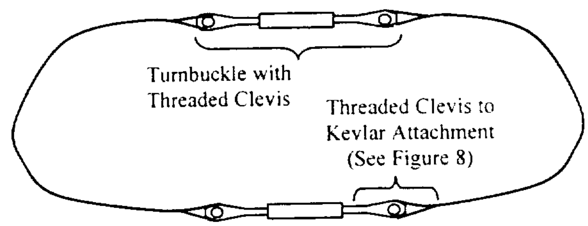

Figure 7: Kevlar Cable Assembly with Turnbuckle

In addition to generating a large strain, the Kevlar cable weave pattern generates a compressive force towards the cord center when tension load is applied (Figure 8). This behavior enables the Kevlar cord to be attached to the turnbuckle with a simple but effective loop that relies entirely on internal frictional forces from the braided pattern. The Kevlar cord is attached to the turnbuckle by looping Kevlar cord end through the clevis and back into the Kevlar cord itself. This design allows the cable assembly to develop its maximum breaking strength characteristics.

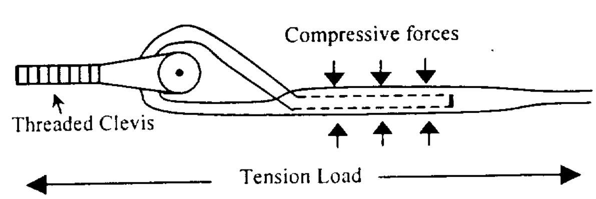

Figure 8: Kevlar to Turnbuckle Attachment

Cable Load Cycling (Preloading)

It is important that the SARRS cable has enough strain to allow the thermal knife to sever the cable properly. The strain helps the cutting action by pulling the Kevlar fibers away from the thermal knife heater element. In addition, a sudden release of strain energy is required to drive the cable away from the spacecraft. It is also important that the cable stiffness is sufficient to develop the tension load within the limits of the turnbuckles travel. A test series was performed to develop a preloading technique that will increase the cable stiffness to satisfy the turnbuckle limits and still maintain adequate strain when tensioned. The technique loads the cable to 70% of its breaking strength and maintains the load for duration of three minutes. The loading is repeated ten times.

Cable Tension Measurement

A standard aircraft cable tension-measuring device (Tensitron, Model ACM-400) was initially used to measure the Kevlar cable tension. This type of tension measuring device is based on a three-point cable deflection method as shown in Figure 9. The results of using this type of device on Kevlar cord were inaccurate and not repeatable. The measurements varied by as much as 17% along one continuous cable section between panels when the tension should be the same. In addition, repeated tension measurements in the same location on the Kevlar cord varied by as much as 10%.

The inaccurate measurements resulted from the measuring device permanently deforming the Kevlar cable. A 'crimp' remained in the cable after the removal of the measuring tool. This 'crimp' indicates that permanent changes had occurred in the cable, effecting the tool's measurement. Stainless steel cables do not have this problem because they behave elastically when a lateral load is applied.

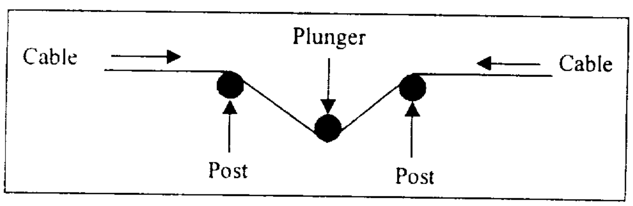

Figure 9: Three Point Tension Measurement

Frictional forces accounted for additional portion of the error in the measurements. The cable does not slide freely around standoffs when tensioned. In addition, the tension increased further when the tool deflected the cable during measurement. A larger increase was found in the cable nearest the standoffs and less in the middle section. These variations found along a continuous cable section accounted for addition errors in the tension measurement. As a result of these issues, an alternative method was developed to measure the Kevlar cable tension.

Tension Measurement Development

A Musical Pitch Method was developed to measure the tension of the Kevlar cables. This method uses an off-the-shelf chromatic tuner with a clip-on pick-up, a type of microphone, to determine the tension in Kevlar cables. Musicians use these tuners to tune musical instruments. The chromatic tuner measures the musical note, or pitch, that emanates from a free section of cable with a fixed end when plucked like a guitar string. The tuner's built-in microphone can measure the pitch, but the clip-on pick-up eliminates the effect of background noise. Music theory assigns a frequency to each musical pitch, so, by measuring the pitch, the tuner measures the frequency of the vibrating cable. A formula translates the frequency to tension based on the section's node length and the cable's mass per unit length.

Equation (1) represents the velocity, v, of a wave along a string with tension, F, and mass per unit length, μ. The assumptions used in the equation include fixed end conditions, no frictional losses due to damping in air, and negligible cable stiffness[1].

$$v = \sqrt{\frac{F}{\mu}} \quad (1)$$

Equation (1) was used to derive equation (2) for tension in terms of frequency, node length, and mass per unit length. The wave velocity relates to the wavelength, λ, and the frequency, γ, of the string by $v=\lambda\gamma$. In addition, $\lambda=2L$, where L represents the node length (distance between standoffs). Equation 2 was used in the Musical Pitch Method to determine the cable tension *(F)*.

$$(2\gamma L)^2 \mu = F \quad (2)$$

Equation 2 represents the general case and does not take stiffness or friction into account. The equation also assumes a uniform strand of cable, whereas the actual cable is formed by a weave of small strands. Through testing, correction factors were determined to compensate for the assumptions made.

Table 1: Musical Note to Cable Tension

Note (cent)	Frequency (Hz)	Tension (N)	Tension lbf
C	523.2	1168	263
C (+10)	526.3	1182	266
C (+20)	529.4	1197	269
C (+30)	532.5	1211	272
C (+40)	535.6	1226	276
C (+50)	538.8	1241	279

Sample musical note to cable tension data is shown in Table 1. The table was developed through testing by applying known tension load to a load-cycled cable sample and measuring the musical note it produced. The conversion table is used to translate the musical pitch to cable tension that is within ±2% of its theoretical value. The musical note is measured by attaching the clip-on pick-up to the cable standoff (Figure 10) and plucking the Kevlar section between the solar panels on the spacecraft. This measurement technique does not permanently deform the cable.

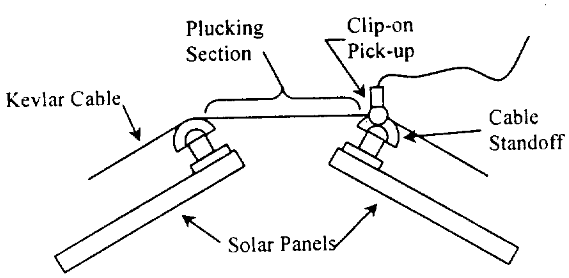

Figure 10: Musical Pick-up Attachment to Cable Standoff on Spacecraft, 1 of 4 Locations

Load Relaxation Tests

The SARRS cable tension requirement was bounded by minimum and maximum values of 200 lbf (890 N) and 300 lbf (1334 N), respectively. The minimum value was required to secure the solar panels and prevent gapping during launch. The maximum value was based on the spacecraft structural load limit resulting from cable tension. In addition, the tension range must be maintained for 45 days on the launch pad and during the launch environment. A series of tests were performed to determine the restraint cable tension characteristics under these conditions.

Time, humidity, and temperature all affect the SARRS Kevlar tension load and relaxation rate. A series of tests were performed to investigate the individual and combined effects that each of these conditions would have on the tension load.

Relaxation Rate Versus Cable Length

The cable assembly has a total unloaded Kevlar length of 300 in. (762 cm). It was not feasible to place this entire length within the available small test chamber, therefore a test was performed to investigate the effect shorter cord lengths would have on the load relaxation rate. Three Kevlar cord specimens of 1, 10, and 20 inches (2.54, 25.4, and 50.8 cm, respectively) were prepared. Each specimen was preloaded to 500 lbf (2224 N) for 30 minutes to remove constructional stretch. The load was reduced to zero and then increased to 275 lbf (1223 N). The relaxation rates were 5.8, 4.7, and 5.2 percent per decade and was not a function of specimen length. Based on these results it was decided to proceed with testing using cable samples that were shorter than the flight cables.

Relaxation From Final Stowage To On-orbit Deployment

Several tests were performed that subjected tensioned Kevlar cable samples to a simulated environment from final cable installation to on-orbit deployment. The initial purpose of these tests was to determine the relaxation rate and final cable tension at the end of the 45-day period. Later, the test was extended to include the launch environment. The goal was to demonstrate that a load-cycled Kevlar cord could maintain a minimum tension of 200 lbf (890 N) during launch environment.

A Kevlar test specimen of 16 in. (40.6 cm) was used in the first test. A typical test fixture with Kevlar cable specimen and load cell is shown in Figure 11. The specimen was preloaded to 500 pounds (2224 N) ten times at three minutes duration and immediately placed in the test fixture at 275 lbf (1223 N). Two days after the initial loading, a relaxation plot (Figure 12) was projecting the cable would not maintain the minimum tension for the required 45-day period. The specimen was reloaded to its initial value and a new 45-day period was started.

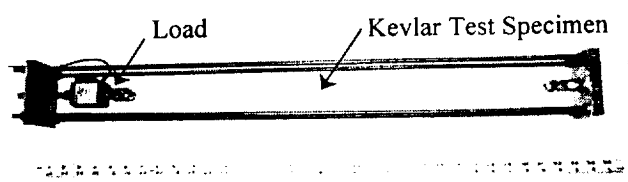

Figure 11: Test Specimen Load Relaxation Test Fixture

During the first 10 days of the new cycle it became apparent that the ambient humidity fluctuations were affecting load relaxation rate. To determine the magnitude of the humidity effects, the specimen was placed in a humidity-controlled ("Glove") box so the tension load could be monitored as a function of relative humidity. Each time the humidity setting was changed the cable load readings would change accordingly at approximately 2.5 lbf (11.1 N) per percent change in relative humidity. At day 24 the relative humidity was set to 40% for the remaining duration of the test. The rate of relaxation during this period was constant.

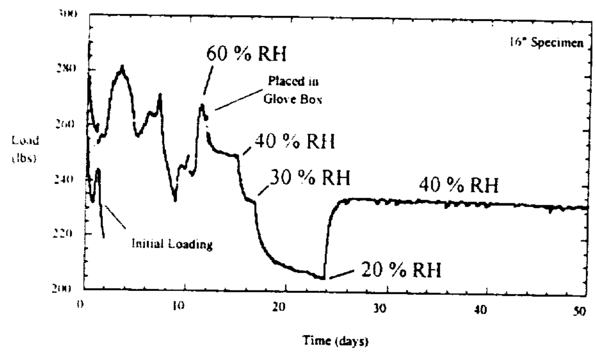

Figure 12: Load Over Time With Varying Relative Humidity

Relaxation Rate Versus Constant Relative Humidity

The MAP spacecraft requires a relative humidity environment of 40% to 60% RH inside the rocket fairing. The 45-day load relaxation test was repeated with a constant relative humidity of 50% RH. Additional spacecraft structure testing and analysis allowed for the SARRS maximum tension value to increase from 300 lbf (1334 N) to 490 lbf (2180 N). In addition, the Kevlar cord was changed to a larger diameter that had a minimum 1000 lbf (4448 N) breaking strength. The increased maximum tension value allowed for higher initial load setting and increased the minimum tension margin.

A test was designed to determine if the SARRS cable initial tension load would affect relaxation rate. Four Kevlar cord specimens (25 in, 63.5 cm) were preloaded 10 times each to 700 lbf (3336 N) for 3 minutes duration. The cables were tensioned to 330, 355, 380, and 405 lbf (1468, 1579, 1690, 1801 N respectively) in a humidity environment of ~ 40% RH. It was noted that prior to placing the specimens in the test chamber the tension was decreasing rapidly. The tensions were reloaded to their initial values three times within a 50-minute period. Each time the specimens were reloaded the relaxation rate decreased. After the third reloading, the specimens were placed in an enclosed environment that maintained 22-24 °C and relative humidity at 50% RH. The tension values were continuously monitored for 45 days and the results are shown in Figure 13.

The loads were plotted verses time on a logarithmic scale. The load increase at day 9 resulted from an error in test chamber humidity setting. From the plot, the rate of relaxation was independent of the initial tension and decreased an average of 5.0 % per order of magnitude. Based on the slope, the restraint cable lost 5% of the initial tension within the first day, another 5% at day 10 and another projected 5% at day 100 after the final reloading. The restraint cable will lose less than 15% of if its initial tension after 45 days.

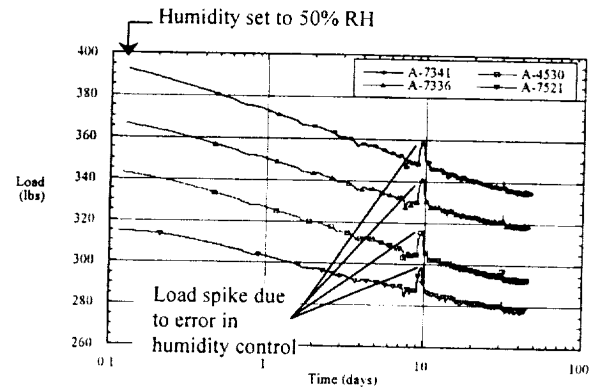

Figure 13: 45-Day Cable Relaxation Rate

Load Change in Vacuum

During launch, the SARRS will experience a change in relative humidity environment from ~50% to 0%. At the end of the 45-day test, the humidity was lowered from 50% to 40%. The results indicated a load reduction of 20 lbf (89 N) and confirmed that humidity will affect the restraint cable even after 45 days under tension.

An additional test to simulate the launch environment was conducted with two Kevlar specimens (25 in, 63.5 cm). The specimens were exposed to full vacuum within 10 minutes (37% RH to 0 % RH) after being preloaded (10 times/ 3 minutes duration) and then loaded to 310 lbf (1379 N). The total load loss for both specimens was 75 lbf (334 N) after 24 hours or approximately 2 lbf (8.9 N) per percent humidity.

Temperature Effects

The SARRS Kevlar cable launch temperature profile is shown in Figure 14. The profile represents the predicted Kevlar cable temperatures during launch and prior to deployment. A test was performed to determine the temperature effects on the SARRS cable.

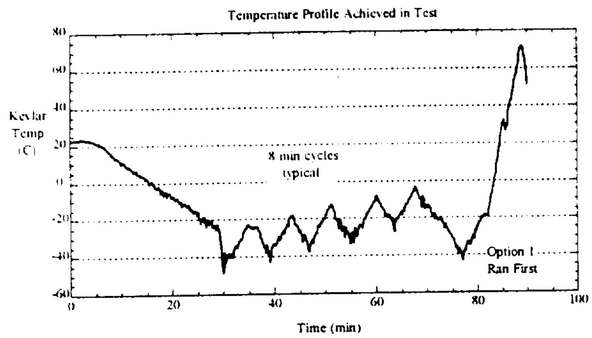

Figure 14: SARRS Cable Temperature Profile

Two Kevlar specimens were load cycled to 700 lbf (3114 N) and subjected to the temperature profile. The resulting loads were plotted in Figure 15.

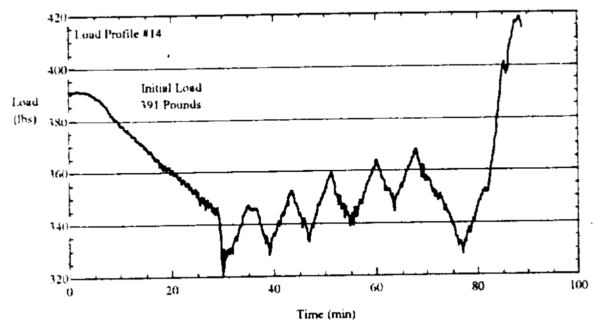

Figure 15: Cable Load Based on Temperature Profile

A typical load versus temperature plot was generated from temperature and load profile data and depicted in Figure 16. Below 40 °C the Kevlar tension changed at a rate of 0.9 lbf (4 N) per degree Celsius. The rate of change above 40 °C is less and assumed zero.

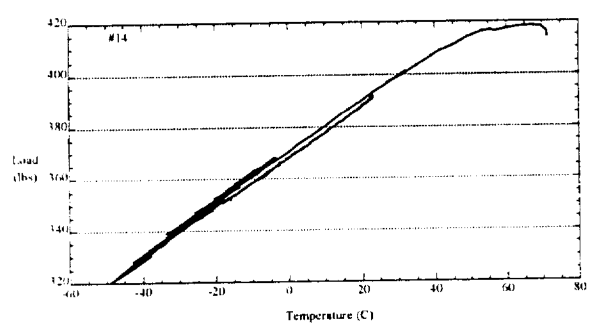

Figure 16: Load verses Temperature

Cable Tension Prediction

There was no access to monitor the cable tension after fairing installation and during the potential 45 days on the launch pad. However, it was possible to estimate the SARRS cable tension at any point from the last measurement to deployment. The calculations were based on the following test results of relaxation rates versus time, relative humidity changes, and temperature.

As an example:

Final Tension	340 lbf (1512 N)
Humidity during final tension	46 % RH
Time on launch Pad	10 days
Humidity during 10 day period	40 % RH
Pad Temperature	18 °C
Orbit Temperature	35 °C
Deployment in 1.5 hours	

The minimum tension during launch would be:

Final Tension	340 lbf (1512 N)
Change in % RH (6 x 2.5 lbf)	- 15 lbf (68 N)
Time on Pad (0.1 x 340 lbf)	- 34 lbf (151 N)
Vacuum (15 lbf (68 N)/ hr)	- 23 lbf (102 N)
Delta Temperature (17 °C)	+ 15 lbf (68 N)
Minimum Tension	283 lbf (1259 N)

Cable Installation

The cable was constructed, preloaded, installed, and tensioned as per a written procedure. Each cable assembly started with two new Kevlar cords approximately 175 in. (4.4 m) in length. The cord ends were looped through the turnbuckle clevis and secured back into the cord itself. The length of each assembly was measured with 5 lbf (22.2N) of tension load applied. The measurement was to ensure the proper dimension for installation and tensioning.

The two Kevlar cords and turnbuckles were joined to form a continuous loop. The cable assembly was loaded by suspending a weight of 1400 lbf (6228 N) through the loop for three minutes duration. The loading was reduced to zero force and repeated 10 times. In addition to pre-stretching the cable, the loading proof tested the integrity of the newly constructed cable assembly loops. After the load cycling, each Kevlar section length was measured to ensure the proper post-stretch length was achieved.

The restraint cable was installed around the stowed solar arrays and tensioned to 350±10 lbf (1557± 44 N) using the two turnbuckles. The turnbuckles were adjusted by alternately turning each an equal number of rotations. The purpose of adjusting in this manner is to minimize the tension differences around the stowed panels. The restraint cable was re-tensioned to its initial load after a minimum of 24 hours.

Deployment Test

A full-scale engineering test unit (ETU) of the Solar Array Deployment System (SADS) was used to perform deployment tests during the SARRS development. The purpose of these tests was to evaluate the SARRS performance under various environmental conditions. Figure 17 shows a typical deployment test configuration.

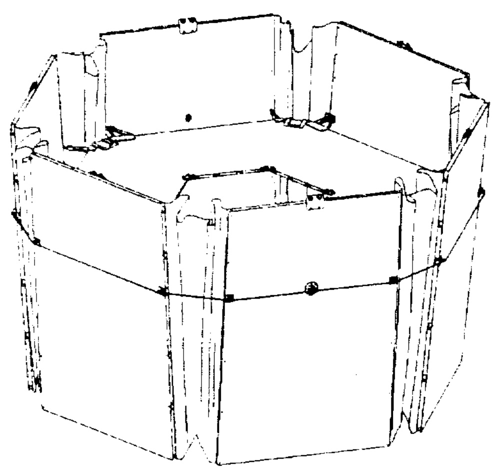

Figure 17: SARRS Deployment Test Setup

The ETU consisted of flight design SADS components mounted to a test structure that simulates the spacecraft structure. A counter weight system was attached at each panel to negate the gravity effects during deployment testing. High-speed cameras captured the cable action as it travels away from the panels. The cable was severed in an average of 22 seconds with nominal thermal knife voltage of 21.0 volts. An evaluation of all video recordings indicated successful cable release.

Thermal Vacuum Deployment

Additional deployment tests were performed with the ETU in a thermal vacuum chamber. The tests were performed at various temperatures in a vacuum environment. High-speed cameras were mounted outside the chamber to capture the initial cable action through viewing ports. The Kevlar cable release action was successful and as demonstrated in the ambient condition test. The average time to sever the Kevlar in vacuum was shorter, by an average of 7 seconds when compared to ambient deployment tests. It is theorized that the shorter cut time is due to higher heater element temperature from the lack of thermal convection.

Conclusion

The development and qualification of the MAP solar array restraint and release system has been completed in time to meet the MAP project schedule. All the requirements were met including a successful deployment on orbit. The SARRS design is based on the use of the thermal knife component and Kevlar cord. The thermal knife was procured as a fully space qualified component. The SARRS engineering development was based on integrating the thermal knife into a new design. The Kevlar cord construction (braid pattern) is not unique to MAP and can be obtained from any reputable Kevlar cord vendor. Acquiring the cable tension by measuring its musical pitch is a new approach. A more in depth account of the development of this approach to measuring Kevlar cable tension will be published in the near future.

Acknowledgement

The author of this paper would like to acknowledge certain individuals and organizations that provided excellent support in the development of the MAP Solar Array Restraint and Release system. To Fokker Space for providing the thermal knife components and technical assistance, to Michael Viens/GSFC for all the Kevlar load characteristic testing and Jason Hair/GSFC for developing the method of obtaining the tension by measuring its musical pitch. In addition, a very special recognition goes to Steve Harper/NSI, contractor mechanical technician, for constructing all test cable samples and providing valuable input into the cable assembly procedure.

References

1. Marion, Jerry B., and Hornyak, William F., "Part 1: Physics for Science and Engineering," CBS College Publishing (1982) pp. 512-519.