ROBUSTNESS IMPROVEMENT OF ARA KEVLAR HOLDDOWN RESTRAINT CABLES

E. Bongers, J. Koning, T. Konink

Dutch Space (an EADS Astrium company), Netherland

Email: [E.Bongers, J.Koning, T.Konink]@dutchspace.nl

ABSTRACT

Dutch Space has developed a Hold Down and Release System based on Kevlar Restraint cables and Thermal Knife release in the early nineties of the previous century. The system has been qualified for application in the company's solar array families ARA and FRED for GEO, LEO, MEO and scientific deep space missions comprising solar panel stacks ranging from 2 to 6 panels. Beside solar arrays, derivatives of the HDRS have been used for antenna, cooler and experiment cover hold down and release. Over 500 HDRS units have performed with 100% success in space.

Today's missions do not differ much in nominal conditions but more extreme failure modes are specified resulting in more extreme temperatures. The restraint cables, which are exposed directly to these limits of the thermal environment, have been upgraded to cope with the new requirements. An extended life time acceleration test program has been defined and executed to demonstrate their robustness.
The qualified upper temperature of the system, the most critical one concerning loads, has been increased from 105°C to 125°C.

The paper will describe problems experienced at high temperatures, the new design, supporting engineering tests, the measurement of tension distribution in the cables with Raman spectroscopy, and the accelerated test program and its results.
Kevlar cables according to this new design are now baseline for solar arrays of the ESA programs Sentinel-1, Sentinel-2, Galileo FOC, EarthCARE and Aeolus.

1. INTRODUCTION

Dutch Space developed a Holddown and Release System for the ARAMkIII solar arrays based on a pretensioned braided Kevlar cable and a redundant Thermal Knife system. The activated Thermal Knife reduces the fibre strength resulting in a gradual snapping of all strands.

A test was planned for the Sentinel-1 solar array end 2010 to qualify the design for a 6-panel version and a higher temperature of the outerpanel holddown point.

An engineering test in vacuum conditions showed a clear fibre failure in the endfitting fixation of the restraint cable.

2. DESIGN AND FUNCTIONING PRINCIPAL

After wing stowage the cable is inserted in the cup/cone stack and tensioned to 7800 N.
That preload is sufficient to keep contact between the cup/cone separation planes during launch (vibration loads, etc.).
The original cable design has aluminium terminations: barrel and spike with the Kevlar fibres clamped in between.
The bottom termination has a bayonet connection to the holddown bracket for easy fixation. The top termination has a thread for adjustment of the preload.

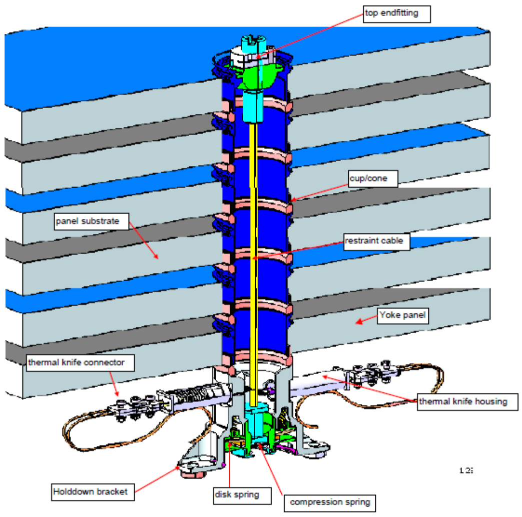

Figure 1, Cross section of a 6-panel Holddown and Release Mechanism

Deployment of the solar array is initiated by a DC command (20V, 0.7A, 60 sec) to the Thermal Knife heating the tip to several hundred degrees C. The high temperature degrades the braided Kevlar fibers which snap under the remaining preload.

For reliability reasons a redundant Thermal Knife is mounted in each Holddown stack.

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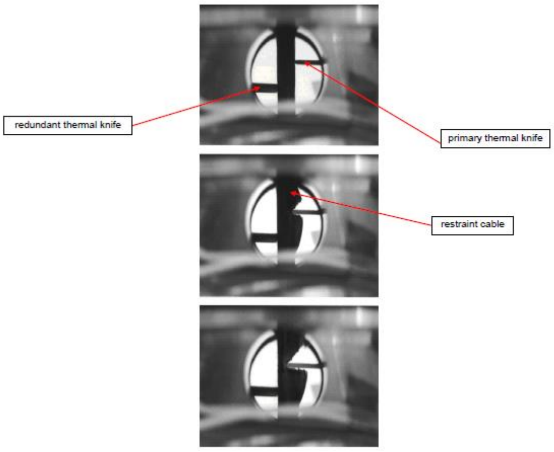

Figure 2, Thermal Knife, degrading a Kevlar Holddown cable

The qualification tests on the original design comprised:

- Ultimate load (UL) tests at cable level
- Shelf life tests (UL after 12 months) at cable level
- Relaxation tests of 9 month (stack level) simulating prelaunch conditions on a pretensioned stack
- Thermal vacuum cycling (20) and cutting in worst case conditions (stack level)
- Hotsoak at stack level in vacuum (72 hrs at 105°C)
- Random vibration

The cables are supplied by Bexco (Hamme/Belgium). Both the braiding of the Kevlar strands and the fixation of the metal endfittings are done by Bexco.
Each cable is proof loaded twice to 10 kN, see figure 3.
With each supplied lot a number of cables are tested to ultimate load (requirement ≥ 14 kN (3σ value)).

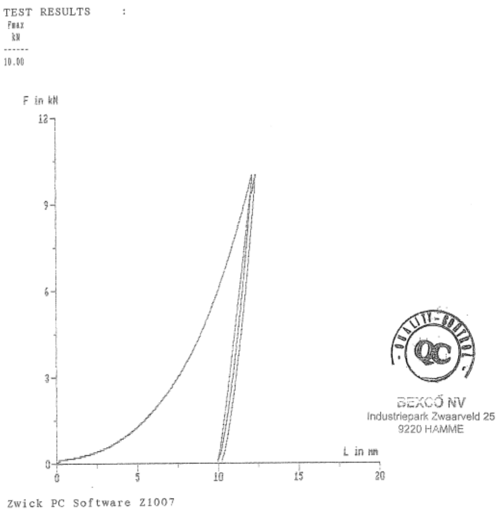

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Figure 3, Proofload curve (10 kN) on cable with 110 mm length (3-panel size).

3. ANOMALY IN ENGINEERING AND QUALIFICATION TEST

The maximum needed qualification temperature for the Sentinel-1 programme was calculated to be 135 °C. This was well above the qualified status of 105°C for a 5-panel stack. The Sentinel-1 design has a 6-panel stack.

Early in the Sentinel-1 programme a hotsoak test was started at 135 °C for the outer endfitting.
When the maximum temperature in that engineering test was reached the preload dropped in steps to 3.5 kN.

Although the mechanical loads in that phase of the mission are minor, the low force will hamper the cutting process. Cutting tests in various worst case conditions show that 4000 N minimum preload is needed for a reliable cutting process.

No production anomaly or test error could be identified. The team concluded that a redesign on the cable was inevitable.

The design was changed on the highest (thermally) loaded area; the endfitting at the upper (fixed to the outer panel).

- The endfitting material was changed from aluminum to titanium.
- The shape of the spike was slightly changed to optimize the compressive load perpendicular to the fibres (rear side loading, thus highest compression forces on the large spike diameter).

With that new design a delta qualification programme was started:

- Thermal vacuum cycling
- Thermal vacuum hotsoak
- Hotsoak testing in ambient conditions
- Relaxation test at ambient conditions

All these tests were finished successfully except for the last one. According to the delta qualification programme 4 stacks were preloaded for 275 day (= 6 month x 1.5 SF) to simulate the prelaunch conditions.

One stack showed a sudden and unexpected force drop after 29 days, see figure 4.
The 3 remaining stacks gave a relaxation as expected and no anomalies for 294 days, showing that the fibre stresses are randomly exceeded in one cable.

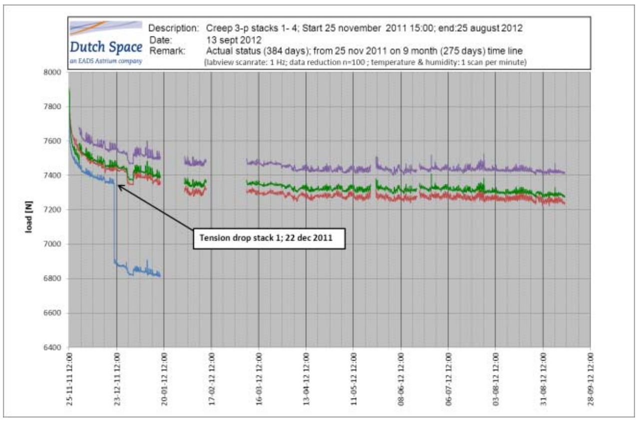

Figure 4, Relaxation test on 4 stacks at ambient conditions

Figure 5, The arrows indicate that the broken strand results in a slight irregularity of the braiding pattern.

The above figure shows the strand irregularity and failure that caused the force drop. Further destructive inspection showed that the strand was broken in the lower endfitting (on left side).

The storage test at ambient conditions was not considered risky because we dealt with a high temperature problem.

4. FAILURE INVESTIGATION

As a standard procedure a root cause investigation was started and the project teams of the relevant customers have been informed.
Customers were informed on the progress and status of actions of the root cause investigation. An AIR (Astrium Investigation Request) was generated.

The cable with a tension drop has been subjected to detailed destructive inspections after dismantling the test setup.
The failure tree was made with 2 branches:

- Root cause is due to a random phenomenon
- Root cause is due to a systematic phenomenon (design or production)

No likely contributor for a random phenomenon could be identified.

The broken cables of the long term storage test showed a broken strand in the aluminum bottom end-fitting (see figure 5).
It was considered likely that the load conditions (tensile stress in fiber direction in combination with high compressive stress perpendicular of the cable) of the broken strand have been too high.

Endfittings are fixed to the braided cable with the 10 kN proofload. Not all strands obtain exactly the same length. It is estimated that the strain may vary ± 10 % in operational conditions. Moreover the crossings of strands are not all equally severely squeezed between the barrel and spike. Figure 6 shows the braided strands that were loaded on high pressure inside the endfitting, with broken fibers in some strands on the right side.

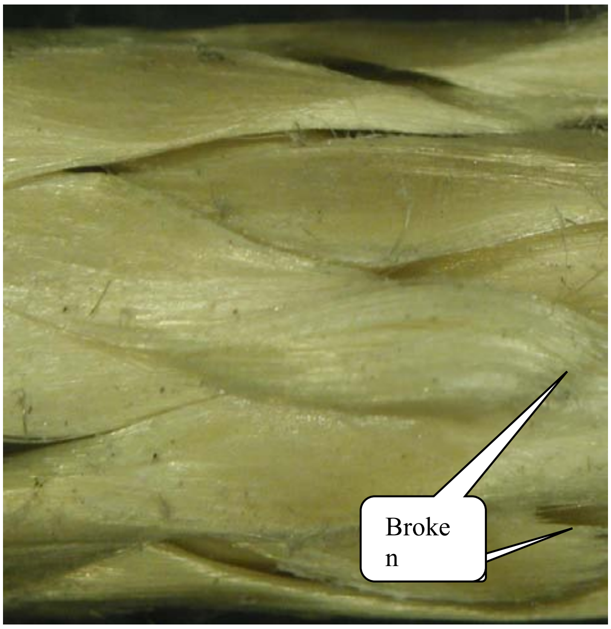

Figure 6, Photograph of the cable after test and removal of the barrel.

Conclusion is that the root cause is systematic or with other words a design issue in combination with the production method.

5. ROBUSTNESS AND DELTA QUALIFICATION TESTS

The team decided to change the design; also the bottom endfitting was redesigned in analogy with the upper endfitting.

It was realized that the amount of statistical test results in the past was poor. The Kevlar polymer is a major part of the stack, so failure of a cable is a function of (pre-) load, temperature and time.
The (pre-) load of 7800 N was not varied, but quite a number of robustness tests at stack level were done to explore the upper temperature limits and time to failure of the design.

The robustness and qualification tests aimed for 2 major objectives:

- Verify that in all fases up to deployment no strand failure will occur.
- Verify that the remaining preload in worst case conditions is sufficient for a reliable cutting. These and earlier tests have shown that 4000 N preload is needed for a reliable cutting process.

The last bullet indicates that for a lower intitial preload the allowable environmental range would be reduced.

The cable load is reduced due the following environments:
- Relaxation in the storage mode, waiting for launch, see figure 11.
- Vacuum, , see figure 8
- Relaxation in the early orbit mode storage mode, waiting for launch, see figure 8
- Thermal cycling, see figure 8
- Cold soak, see figure 8

All these impacts have been quantified.

The robustness test results on 3-panel stacks are summarized in figure 7.
Four stacks were subjected to a steady temperature field. The holddown bracket was actively controlled at either 50°C or 75°C. The temperature of the outerpanel endfitting was controlled to temperatures between 85°C until 155°C, shown on the horizontal axis. The test was continued until a pretension drop (>300 N) was measured. The time until failure (vertical axis) is identified with a marker.

Tests in vacuum were performed on single stacks. These confirmed the results in ambient pressure conditions.
The relaxation test at room temperature, which is considered part of the qualification tests, is also plotted. The blue vertical line inducates the duration of the test, see figure 7.
The red dashed line (figure 7) indicates the period until breakage, that is considered necessary for current and future projects.

This method of plotting is based on the supposition that the chemical bond failure time of the Kevlar fibres follows the Arrhenius equation.
The Arrhenius equation gives "the dependence of the rate" constant k of chemical reactions on the temperature T (in Kelvin) and where A is the pre-exponential factor or simply the prefactor and R is the Universal gas constant.

$k = Ae^{-E_a/(RT)}$ chemical bond failuretime as function of the absolute temperature

The time to failure data (log scale) presented in figure 7 shows more or less a linear relation with 1/T [K^{-1}].

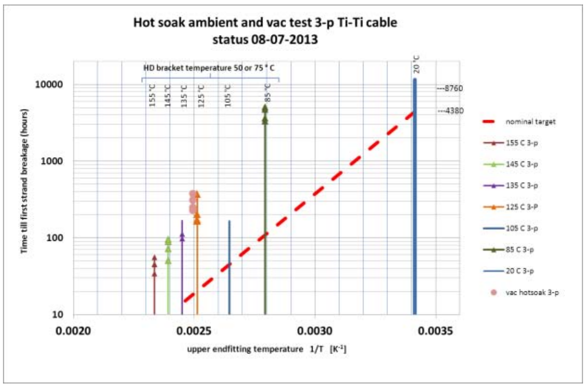

Figure 7, Robustness tests on a 3-panel stack

Similar tests were done for the 6- and are running for the 2-panel stacks.

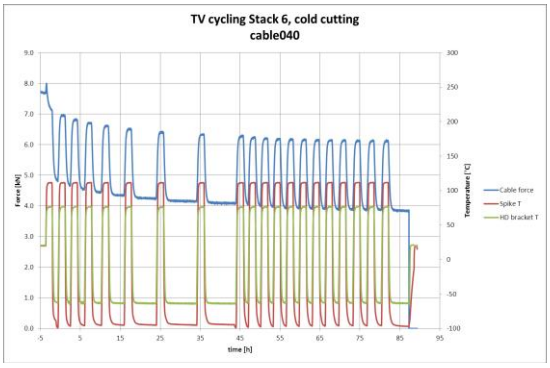

Figure 8, Thermal cycling test (20 cycles) on a 3-panel stack finalized by cutting in cold conditions.

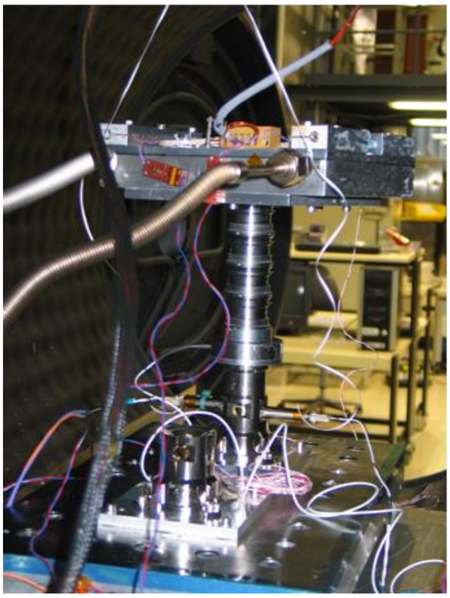

Figure 9, Set-up for 6-panel stack for hot- and cold soak in vacuum

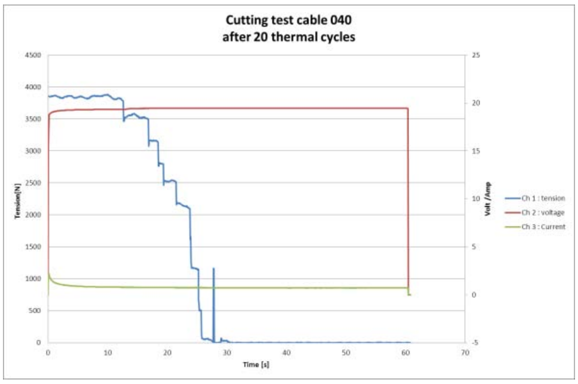

Figure 10, cutting test in cold condition after 20 thermal cycles

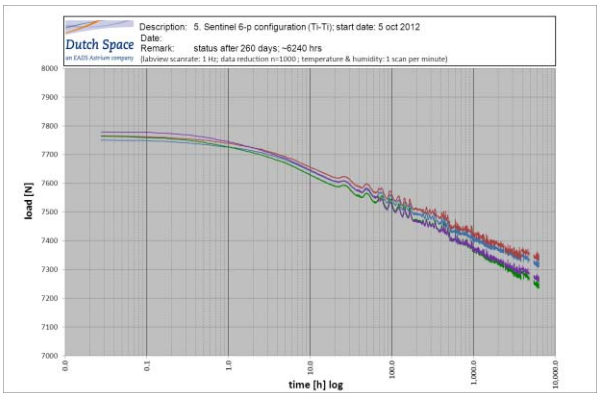

Figure 11, Relaxation test, qualification of 6-panel cable on 4 stacks

6. ABAQUS ANALYSIS

An Abaqus Finite Element model was made of the top and bottom endfitting.

The bottom endfitting is a bayonet connection, so asymmetric. Both a rotatory symmetric and a 3-dimensional FEM model were made. The 3-d model analysis appeared to suffer from converging problems.
The process of insertion of the spike, cable release and proofloading and the thermal environment are simulated. This is a highly non-linear behaviour based on friction.
Both the old aluminum design (barrel and spike) and the new titanium design were analysed.

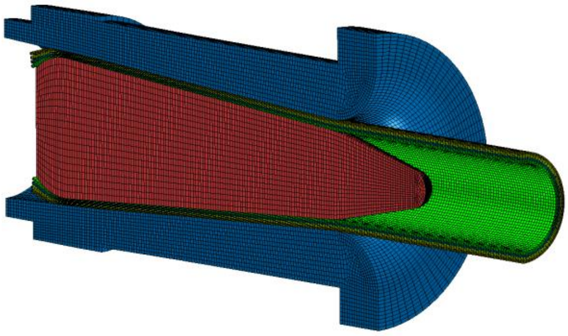

Figure 12, Model of barrel, Kevlar cable and spike

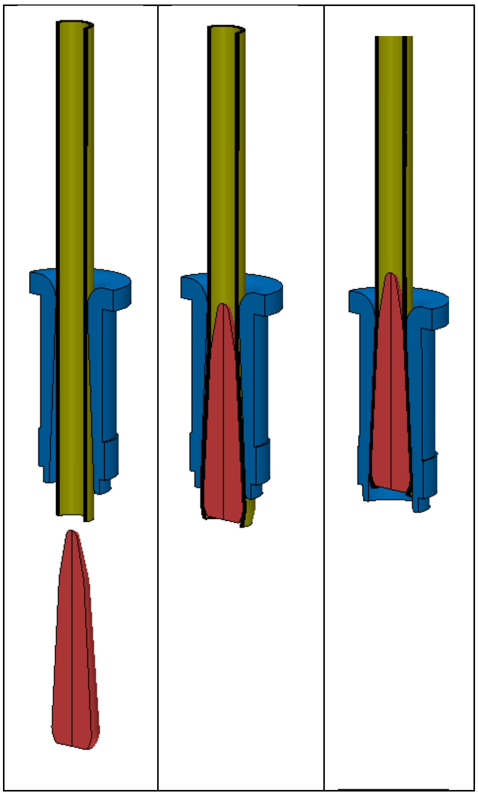

Figure 13, Modelling of assembly phases

Creating a FE-model is difficult because the braided Kevlar cable is a complex shape. Kevlar properties are partly unknown, estimated material properties perpendicular to the fibres had to be used.
The location of maximum contact stresses corresponds with the inspections on the cables tested to failure.

7. RAMAN SPECTROSCOPY

The production method of joining the endfittings to the braided cable cannot avoid that strands have a different lengths. The shortest strands will see the highest strain/stress and are prone to breakage at high mechanical /thermal loads.

Raman spectroscopy was identified as a method to measure the fibre strain.

Cosine (Leiden/ Netherland) succeeded to build a set-up that could measure the Raman peak shift as function of the fibre tension.

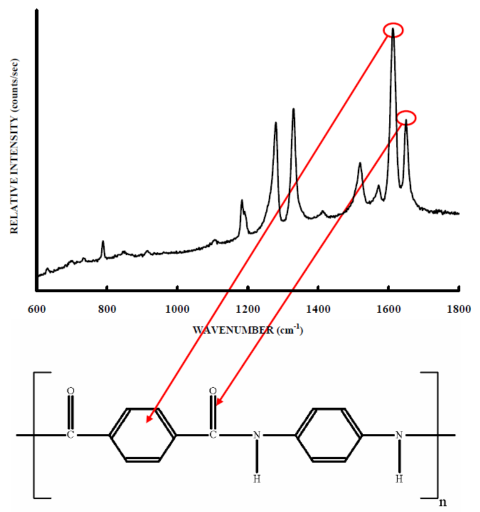

Figure 14, Raman spectrum of the non-tensioned Kevlar cable.

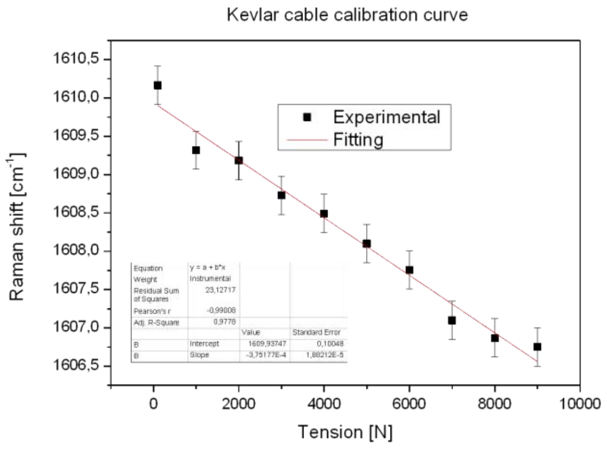

Figure 15, Characteristic curve of the tensile behaviour of the Kevlar cable (Raman peaks position difference v.s. applied tension)

The first data confirm indeed that there is a difference in the strain between different cable strands in the order of what was expected.

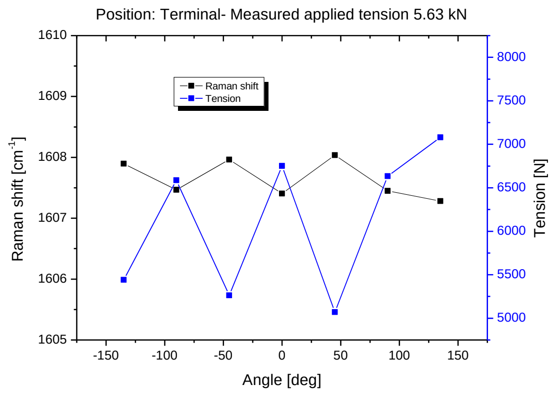

Figure 16, Preliminary Raman results on 7 positions in circumference close to the endfitting, total pretension is 6.12 kN.

The set-up is not yet fully operable. It is the intention to explore production variations in more detail and to identify differences between long and short cables.

8. THERMAL DESIGN AND ANALYSIS

For the observed cable anomalies the temperature and the time (time line) are the variables. The stack preload is not a variable because reducing the preload was not an option for the running and future solar arrays

Three actions were taken for the running and future programmes to coop the cable anomaly.

1. Vacuum tests to verify the conduction path properties in the TMM (Thermal Mathematical Model).
   Thermal Balance tests on a generic test sample (see figure 17) to verify the optical properties of the outerpanel area and to validate the TMM of the complete HD stack.
   No major modifications were found, but some of the uncertainties could be reduced
2. A refined holddown thermal model was made and a detailed thermal analysis was performed on the holddown stacks for the running programmes, focussed on the extreme temperatures.
3. Where needed and possible the thermal design was optimized. OSR's were bonded around the outer panel holddown points. Moreover a white cap was installed. Both measures reduce the maximum temperature.
4. Customers were requested to let the outer panel deliver power in the stowed phase that reduces the outerpanel temperature.

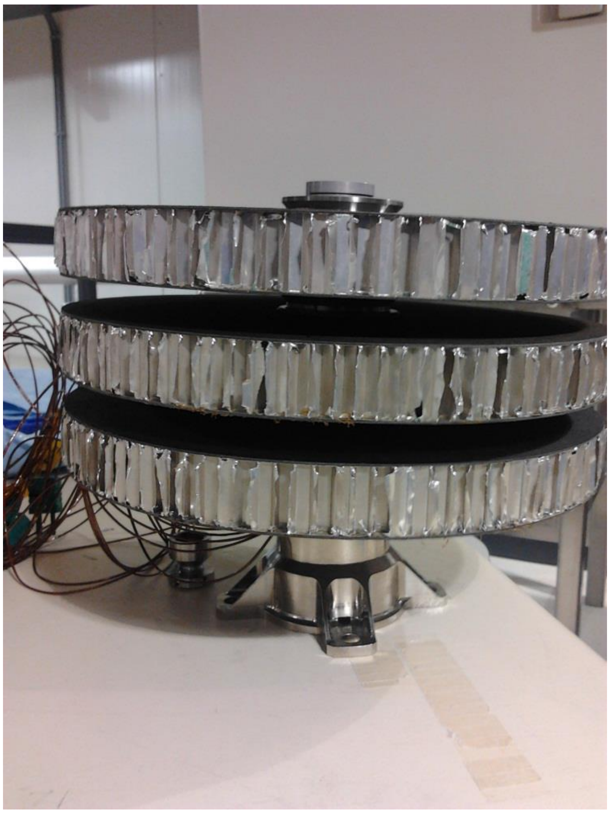

Figure 17 Test item for thermal balance tests

9. REFERENCES

1. Washer, G., Brooks, T., and Saulsberry, R. (2009). "Characterization of Kevlar Using Raman Spectroscopy." J. Mater. Civ. Eng., 21(5), 226–234.

2. Cosine, Technical note 02, Laboratory demonstration of Kevlar tension measurements with Raman spectroscopy.

3. DS-OE-RP-2010-0025 Issue 1 Summary on development of Kevlar restraint cables

4. DS-OE-RP-2012-0042 issue 1 HDRM thermal balance test report

10. CONCLUSIONS

The root cause of the anomaly is systematic or with other words a design issue in combination with the production method.

The redesigned Kevlar cable with titanium endfittings (barrel and reshaped spike) has a much better performance in hot environment.

The holddown stack Thermal Mathematical Model was verified with among others a Thermal Balance test. Some of the uncertainties in the parameters could be reduced.

The running programs have taken proper measures to reduce the maximum temperature extremes:
- Refinement of the holddown thermal model
- Application of OSR and white cap when needed and possible

A good dialogue was maintained between suppliers, Dutch Space and customers to modify the design and to maintain the satellite test and launch schedules.

Dutch Space appreciated the support of NSO (Netherlands Space Organisation)