QUALIFICATION OF THE SEPTA®24 HIGH POWER SADA

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ABSTRACT

The SEPTA®24 is a new Solar Array Drive Assembly (SADA) designed for high power transfer up to 19.0 kW for geostationary applications with 15 years in-orbit lifetime. The SEPTA®24 design is based on a modular concept allowing eight different configurations with and without embedded Electronics.

The purpose of this paper is to summarise and present the tests performed in frame of SEPTA ®24 development and qualification programme.

1. INTRODUCTION

At the end of 2006 RUAG SPACE started the development of SEPTA®24 with the following objectives:

- to design a slip ring for the operation in severe thermal environments;
- to produce a QM model and undertaking a qualification program on the unit.

Since the SADA has to withstand the severe thermal environment associated to the full power transfer, extensive development/validation tests have been carried out at component level in order to optimise the key design feature of the Slip Ring Assembly (SRA) like brushes and brush holders, SRA rotor, thermal filler, adhesive bonding etc.

The qualification test campaign on the SEPTA®24 QM – built up in the configuration including two power SRAs, one signal SRA and the embedded Electronics – has been successfully completed including the lifetime test and the post strip down is currently on-going. The initial functional tests showed excellent electrical performances of the SADA in terms of electrical noise in the power and signal lines, potentiometer accuracy and repeatability of the reference sensor. The QM also withstood the specified high vibration and shock qualification levels without any degradation of the mechanical and electrical performances.

A specific test setup was designed to carry out the thermal characterisation simulating the real hot and cold operating conditions of the SADA in orbit. In fact, this setup allows the control of the temperature at four different thermal interfaces independently. Three different power supply units were used to fully simulate the power transfer from the Solar Array, including 100 V electrical potential between forward and return lines. The thermal balance tests demonstrated that the SEPTA®24 can withstand the severe thermal environment during operation in GEO orbits with the full power transfer.
The lifetime test demanding 14000 full output revolutions was carried out with the same TV test setup mainly in hot conditions and with full power transfer. No significant degradation of the electrical and mechanical performances was observed throughout the whole lifetime.
A change of the motor margins in the cold case have been measured at EOL. Extensive tests in different cold operating and non-operating conditions were performed on the QM in fully assembled as well as partially stripped configuration.

The post strip down activities will provide conclusive results on this change of the internal resistive torques.

2. BRIEF SADA DESIGN DESCRIPTION

The SEPTA®24 Solar Array Drive Assembly follows a modular concept and can be combined in eight different configurations that comprise:

- One stepper motor available in two motorisation options;
- One or two power SRAs (developed by RUAG SPACE Nyon) using gold-to-gold technology
- One signal SRA (developed by RUAG SPACE Nyon) also using gold-to-gold technology;
- With or without embedded Solar Array Drive Electronics (SADE);
- Two different mechanical interfaces to the S/C.

Due to this SRA modular design flexibility, the number of power transfers can be adjusted according to the needs of each platform which results in reduced mass.

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The SEPTA®24 is capable to transfer a maximum power of 19.0 kW per mechanism when supplied by a 100V source.
The SEPTA®24 Qualification Model – built up in the configuration including two power SRAs, one signal SRA and the embedded Electronics – is shown on *Figure 1*.

Figure 1: SEPTA®24 SADA (QM)

Depending on the configuration, the mechanism mass will be between 6.7 and 8.2 kg. The mass for the QM configuration described above is 8.2 kg.

The rotation is carried out in steps of 0.00625°, and varies according to the different operating modes that are defined by ground control. The nominal speed is one rotation every 24 hrs. The mechanisms is however capable of operation at full performance from zero rate up to 20 revolutions per day (5°/min) as acquisition mode speed.
A sketch of the SEPTA®24 SADA is presented on Figure 2 and a general description of the main components is given in the following paragraph.

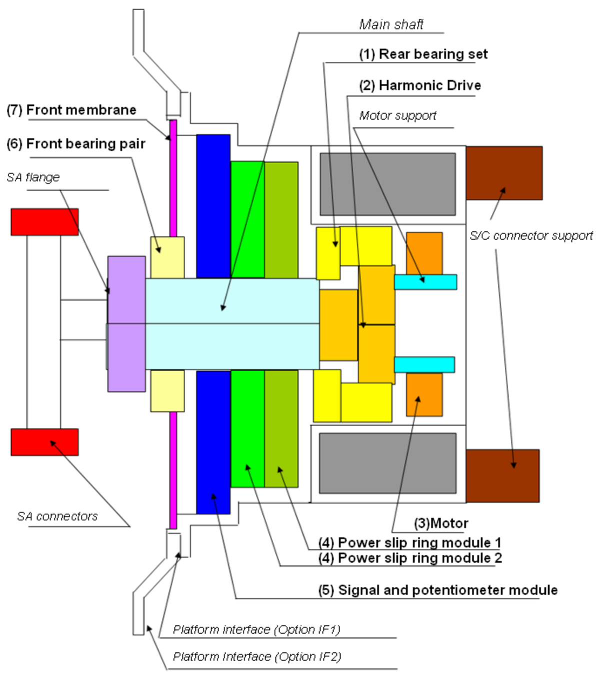

Figure 2: Configuration of the SEPTA®24 SADA

2.1. SADA Main Components

(1) Rear bearing set:
The rear bearing set consists of two hard-preloaded bearing pairs.
One bearing pair is used as rear bearing of the main shaft (slip ring shaft). The other bearing pair is designed such that it provides the required stiffness to hold the motor rotor without any additional bearing.
Both rear and motor bearing pairs are lubricated with PFPE oil based grease.

(2) Harmonic Drive Gearbox:
The Harmonic Drive gearbox used in the SEPTA®24 SADA is the type CSD 20-160 with a customised rotor interface. This Harmonic Drive has a reduction ratio of 160 allows a very small output step.
Creep barriers, wet lubrication (PFPE oil based grease) and retainer impregnation are applied.

(3) Motor
Two stepper motor options can be used in the SEPTA®24 SADA:
- One with a coil resistance of 76 Ohms
- One with a coil resistance of 285 Ohms normally used for all SADA configurations with electronic).

(4) Power Module:
The power SRA is designed for the high power transfer between the SA wing and the S/C. One or two power module can be mounted in the SEPTA®24 SADA.
Two possible versions of the power module can be manufactured and delivered to the final Customer:
- 18 independent lines defined for a transfer current of 10 A each.
- 24 independent lines defined for a current of 7.5 A each.

Both versions have the same mechanical interfaces and the same number of wires on SA and S/C side.
The wire bundles on SA side coming from the first module can be routed through the rotor of the second one. In the same way, the wire bundles on S/C side coming from the second module can be routed through the stator of the first one.

(5) Signal Module:
The signal module is designed for the signal transfer from the SA wing and the S/C in both directions. Basically the signal module consists of:
- 34 lines designed to transfer signals up to 0.5A.
- 2 lines designed for grounding of the SA wing (up to 1A).
- 2 potentiometers (main and redundant).
- 2 Reset switches (main and redundant).

This design allows a clear separation between power lines and signal lines.

(6) Front bearing pair:
The front bearing pair is a hard preloaded ball bearing lubricated with a PFPE oil based grease.

(7) Front Membrane:
This membrane is used in order to link the front bearing pair to the main housing. The main function of this membrane is to avoid the thermo-elastic stresses induced by the thermal gradient between rotor and stator subassemblies during operation in the worst cold and hot cases.

3. SADA QUALIFICATION TEST FLOW

The qualification test programme, which was carried out on the SEPTA®24, is presented on *Figure 3* and included two main phases:

- Development tests on the critical SRA components as validation tests of SRA design features as well as of material and processes
- Full qualification campaign on the SADA QM including Thermal Characterisation tests for thermal design validation and lifetime in vacuum performing 14000 full output revolutions.

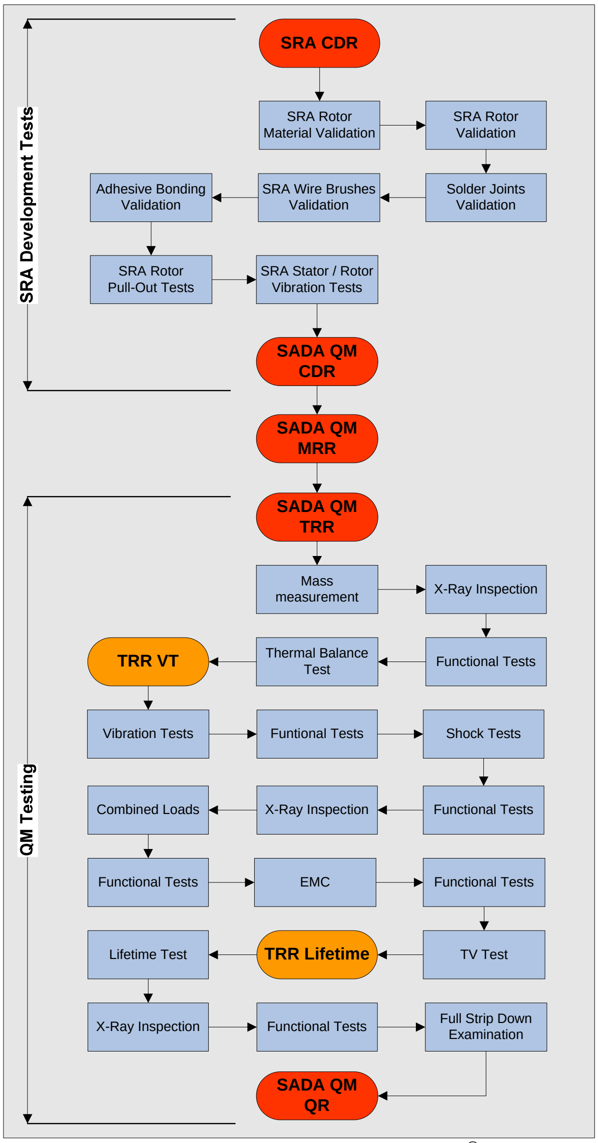

Figure 3: Test Programme for SEPTA®24 QM

The SRA development testing of critical components (such as wire brushes, adhesive bonding, solder joints…) although contributing significantly to the development schedule and project development costs, enabled the risk mitigation during SADA qualification. These tests were aimed to optimise the design of such critical SRA components as well to validate the materials and processes used in the SRA for use in a severe thermal mechanical environment.

The development testing included the following tasks:

- Validation of the resin used for the SRA rotors; these tests included full material characterisation (electrical properties, thermal and mechanical properties…) TV cycling and outgassing tests;
- Validation of the SRA rotor design including TV cycling, vibration and shock tests;
- Validation of the solder joint in terms of solder alloy used for high temperature application as well as of the joint design; these tests included thermal cycling and thermal balance up to 175 °C;
- Validation of wire brushes design including TV cycling and vibration tests;
- SRA rotor pull-out tests;
- TV cycling and vibration tests on SRA stator and rotor.

After this first development testing phase which led to significant improvement of the critical SRA features, a SEPTA®24 QM was finally built and used for the full qualification which included:

- Full functional and performance characterisation at ambient;
- Vibration tests up to 18.4 G_{RMS} along each axis;
- Shock tests up to 2000 g along each axis;
- EMC tests;
- Thermal characterisation in vacuum for validation of SADA thermal design;
- TV tests including functional tests and motor margin tests
- Lifetime test including functional tests and motor margin tests performed every 1000 cycles
- Full strip down examination

The results from the tests that were performed in the frame of the SEPTA®24 qualification programme are presented in following paragraphs.

4. SRA DEVELOPMENT TEST RESULTS

4.1. SRA Rotor Resin Validation

The aim of these tests was to validate the epoxy resin used in the SRA rotor for application in severe thermal and mechanical environment.
The tests showed an excellent stability of the SRA rotor resin in terms of dielectric strength, thermal cycling as well as outgassing. Moreover, the high glass transition temperature makes this material suitable for

applications in severe thermal environments such the SRA rotor (high power transfer in the worst hot case). The following table summarise the test results.

Characterisation Test	Results
Mechanical Properties	σ_{ult} > 145 MPa ε_{ult} < 3% E > 7.0 GPa
Electrical Resistivity (dynamic dielectric strength)	No current [µA] measured between -50 and + 160 °C
CTE Characterisation	Longitudinal: $40.4 \cdot 10^{-6}$/°C Transversal: $63.3 \cdot 10^{-6}$/°C
Rheometric Solid Analysis	T_g > 220 °C E_l (at T_g) > 4.0 GPa
Outgassing (up to 150 °C)	TML < 0.46% RML < 0.13% CVCM < 0.01%
Thermal Cycling in Vacuum (between -65 and +150 °C)	After 100 cycles no cracks or signed of overheating were observed

Table 1: SRA Rotor Resin Properties

4.2. SRA Rotor/Stator Validation

These tests aimed to prove the SRA rotor and stator design as risk mitigation tests. These test included the following:

- Vibration tests (up to 92 G_{RMS} in out of plane and up to 56 G_{RMS} in out of plane);
- Shock tests (up to 2000 g);
- Electrical checks and visual inspections after vibration and shock tests;
- TV cycling (between -50 and +140 °C) followed by electrical checks and visual inspections.

The visual inspection and functional test after vibration and shock as well as after TV tests have shown no damaged on the mock-up. In particular, no delamination of the tracks due to the temperature stress has been observed. Therefore the tests provided confidence in using the epoxy resin in the design of the SEPTA®24 power modules.

4.3. Solder Joint Validation

These development tests were performed to validate the use of the selected solder alloy within the SRA rotor design up to 160°C.

Seven series of six samples each – reproducing the soldering joints rotor track/wires (see *Figure 4*) – were made. Each sample held one solder joint which was tested. On twelve samples, a thin layer of epoxy adhesive was applied on the top surface at the end of the assembly. This layer covered the solder.

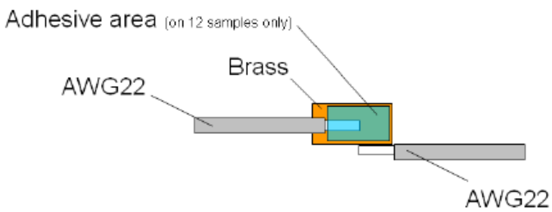

Figure 4: Solder Joint Sample Configuration

The samples were subjected to the following test programme:

- Initial Resistance measurement (at ambient temperature);
- Thermal balance and interval resistance measurement (at 175°C);
- Final Resistance measurement (at ambient temperature);
- Pull-out test;
- Thermal vacuum cycles between -55 and +160 °C and continuous resistance measurement;
- Cross-section of one sample and inspection

Six samples were used as reference and were only subjected to resistance measurement and pull-out test.

The electrical measurements showed that no degradation occurred after period of 6 months at 175°C as well as after several thermal cycles between -55°C and +160°C.

The pull-out tests performed on all the samples also showed that no degradation of the solder joint after a period of 6 months at 175°C as well as after the thermal cycling took place.

For almost all samples the weakest point was identified to be the wires and not the solder joint as shown in *Figure 5*. For those samples where the solder joint was broken, the required pull-out force was much higher than the minimum specified.

Figure 5: Solder Joint Sample after Pull-Out Tests

All performed tests confirmed that the solder alloy as well as the solder joint design was suitable for application in the SRA rotor.

4.4. Adhesive Bonding Characterisation

The aim of these tests was to determine the lap shear strength of the adhesive bonding (epoxy glue) used at different interfaces within the SRA.

For this purpose, different samples in terms of material pair combinations were made corresponding to the adhesive interfaces in the SRA. These samples were tested under different temperature conditions. The *Table 2* hereafter shows the different test configurations and the number of sample which were tested for each configuration.

Material Pair Sample	RT	120 °C	140 °C
Aluminium/ Rotor Resin	x 3	x 3	x 3
Rotor Resin/ Rotor Resin	x 3	x 3	-
Rotor Resin/ Brass	x 3	x 3	x 3
Arlon /Arlon (for brush holders)	x 6	-	x 6

Table 2: Adhesive Bonding Test Configurations

Since the thickness of the adhesive bonding might have an influence on the lap shear strength, a special tool was used during manufacturing of the samples to fix the adhesive thickness to 100 microns (as in the SRA).

The results for the material combination aluminium/ rotor resin are shown on *Figure 6*.

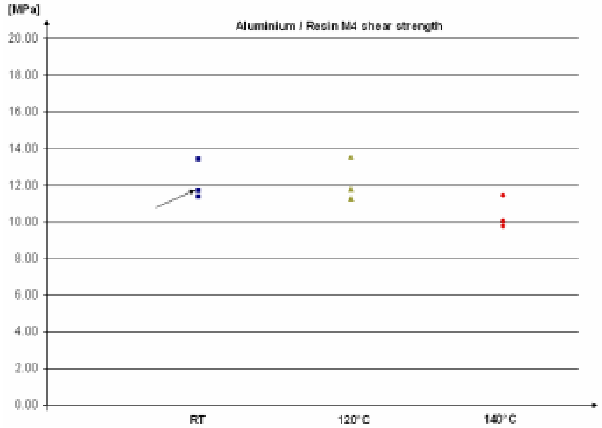

Figure 6: Aluminium on Rotor Resin Lap Shear Tests

It can be seen that a slight decrease in the lap shear strength occurs at high temperatures. Similar results were observed for the other material combinations.

The lap shear strength values obtained are far above the stresses induced by vibration loads as well as by thermo-elastic effects during SEPTA®24 SADA operation in hot conditions.
Therefore the tests proved the suitability of the selected epoxy resin in the design of the SEPTA®24 slip ring modules.

5. SADA QUALIFICATION CAMPAIGN

The development tests performed at SRA component level described in chapter 4 provided the required level of confidence to build the SEPTA®24 Qualification Model to be subjected to a full qualification campaign.
In the following paragraphs the results of the tests performed on the QM are presented.

5.1. Mechanical Pointing Accuracy

The SEPTA®24 SADA showed excellent mechanical pointing accuracy performances throughout the whole qualification campaign.
Figure 7 shows that the coning error remained constant after vibration and shock tests as well as after the lifetime. It can also be seen that the maximum coning deviation is well within the requirements of less than 0.20 deg.

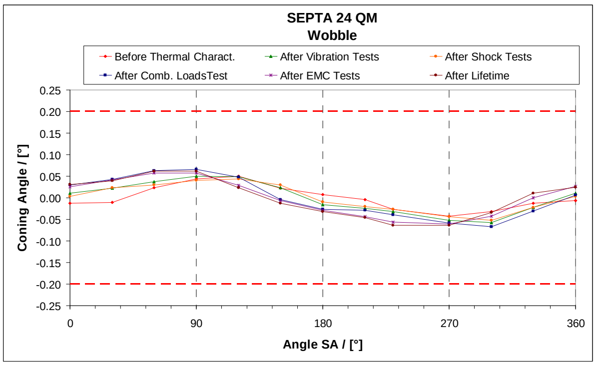

Figure 7: SADA Coning Error

As shown on *Figure 8*, also the concentricity error is far below the specified limit of 0.15 mm and that no change was observed after the mechanical environment tests as well as after the lifetime.

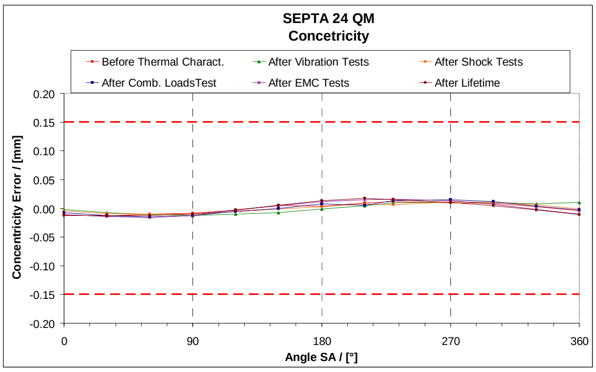

Figure 8: SADA Concentricity Error

5.2. Electrical Performances

The accuracy and electrical noise of the potentiometers as well as the repeatability of the reset switches has been measured against a reference optical encoder with an accuracy of less than 0.001 deg.
As shown on *Figure 9*, the accuracy of the potentiometer is within the required limit of 0.5 deg, and the electrical noise is less than 0.1 deg. No degradation of the potentiometer accuracy and noise was observed after the mechanical tests (vibration, shock and combined loads).
From the TV tests it can be concluded that the accuracy as well as the electrical noise of the potentiometers is only slightly dependent on the temperature and on the vacuum conditions.

The reset switch showed also excellent performances in terms of repeatability, which was measured as less than 0.01 deg.

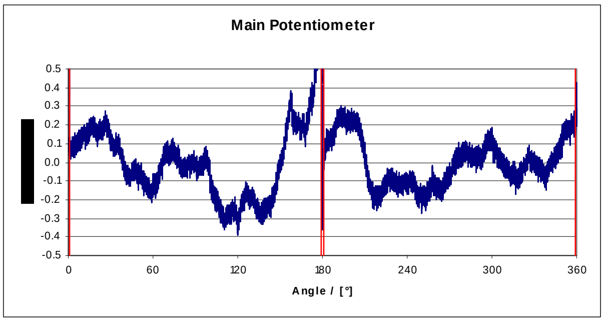

Figure 9: Potentiometer Accuracy

Figure 10 and Figure 11 show the electrical noise (RMS values) measured in both power and signal SRAs. The measured values are far below the allowed limits of 5.0 mV_{RMS}/A for the power SRA and of 10.0 mV_{RMS}/A for th e signal SRA and insensitive to different temperature conditions.

For the power SRAs a s light run-in effect can be noticed in *Figure 10*. This effect is normal for the gold-to-gold contact technology used for the wire brushes especially going from ambient to vacuum conditions as already observed in other SADMs produced by RUAG SPACE. This can be ex plained as dry lubrication effect of the gold coating, which is m ore effective under vacuum conditions.

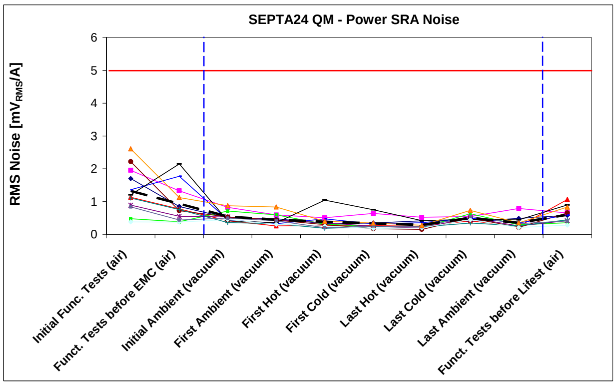

Figure 10: Power SRA Noise (RMS Values)

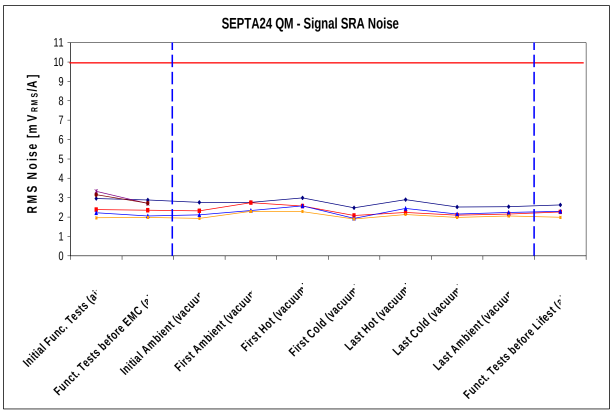

Figure 11: Signal SRA Noise (RMS Values)

5.3. Thermal Characterisation and TV Tests

A specific test setup was d esigned to carry out the thermal characterisation of the SEPTA®24 QM as well as the TV tests and the lifetime. The test set up allows for the tem peratures at the follo wing four different thermal interfaces to be controlled independently:

- S/C interface flange
- S/A interface flange
- Radiation environment for SADA (achieved by using a shroud)
- SA connectors

In order to be fully representative of the power transfer in orbit, an electrical potential of 100 V between forward and return lines was also applied. Therefore, all thermal cases performed during the thermal vacuum tests were cl ose to the real hot and c old operating conditions of the SADA in orbit (including qualification margins).

The qualification operati ng limits are p resented in *Table 3*, whereas the TV cyclin g profile is sh own on *Figure 12*.

	Worst cold start-up case	Worst cold op. case	Worst hot op. case
S/C interface (Ywall)	-35 °C	-30 °C	+65 °C
S/C Internal Radiative Environment	-35 °C	-30 °C	+60 °C
SA Interface	-40 °C	-35 °C	+110 °C
SA Connectors	-40 °C	-35 °C	+75 °C
Line Current	no	7.5 A	7.5 A
Motor Dissipation	no	yes	yes

Table 3: SADA Qualification Temperature Limits

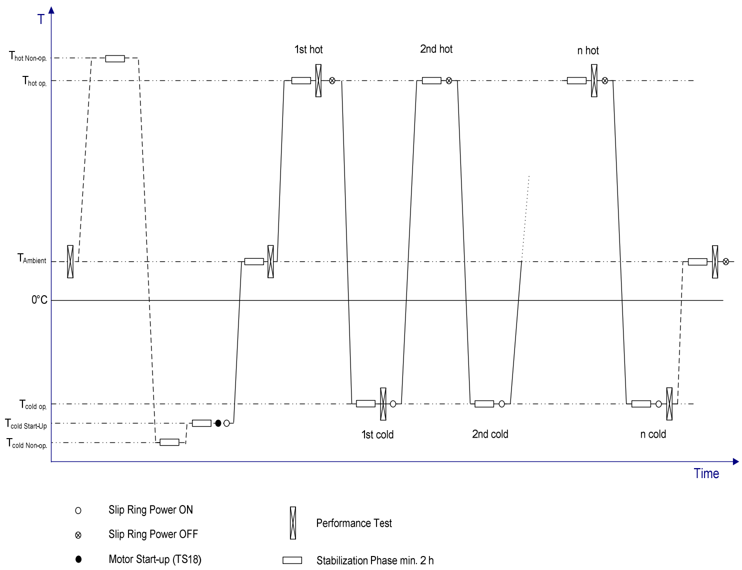

Figure 12: TV Cycling Tests

Due to the high power transferred in such limited volume, the worst hot operating case was considered

the worst case in terms of maximum allowable temperatures of materials used in the SRAs.
Therefore the final thermal hot operating condition was reached step by step increasing either the interface temperatures at SA and S/C flanges or the current transferred in the slip rings.

The thermal characterisation demonstrated that in the worst hot case conditions (including the qualification margins) the SEPTA®24 SADA can transfer the required current levels since temperatures were within the allowed limits for all critical components and below those ones predicted by the thermal analysis.
The electrical resistance for each power and signal lines was also measured during the thermal balance and TV tests in order to derive the power dissipation in the SRAs. In the worst hot operating case the maximum the total power dissipation measured during the TV tests was about 60 W, which is far below the maximum allowed of 80 W.

6. LIFETIME

The lifetime test was carried out under TV conditions for a total of 14000 full output revolutions (including ECSS margins) in the same TV test setup described in chapter 5.3 according to the following sequence:

- 1000 revs in air of which the first 800 were performed with the SRAs unpowered;
- 12000 revs in the hot operating case with the full power transfer in the slip rings;
- 1000 revs in cold operating case with the full power transfer in the slip rings.

Before starting the life cycles in hot conditions a non operating TV cycle and an operating TV cycle was repeated in order to confirm the electrical performances as well as of the motor margins measured during the TV tests.
In order to simulate the real operation of the SADA in geostationary satellites, all revolutions during the lifetime were performed only in one direction including the additional cycles needed for the functional tests and for the motor margin measurements.
Functional tests including SRA voltage drop measurements, potentiometer and reset switch verification tests and motor margin measurements were performed every 1000 revs for the hot cycles and every 500 revs for the cold cycles.

In the following paragraphs the main findings of the lifetime tests are presented.

6.1. Electrical Performance Evolution

During the lifetime the SADA confirmed the promising electrical performances measured during the initial functional tests as well as after mechanical environment tests and during the TV tests.
As shown on *Figure 13*, the power slip ring electrical noise remained fairly constant and far below the requirement during the 12000 cycles in hot operating conditions. An increase of the noise in some lines was observed during the last 500 cycles in cold operating but still within the required limits. During the last ambient cases this noise stabilised to the values measured after the cold cycles.

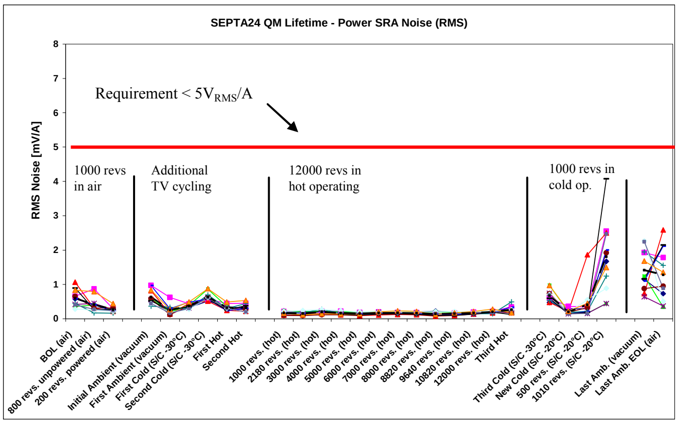

Figure 13: Power SRA Noise (RMS Values) Evolution during Lifetime

As shown on *Figure 14*, there was no increase of the electrical noise during the last cold cycles as observed in the power slip rings. This difference might be due to the fact although the gold-gold technology used in the slip rings is the same, the current level transferred in the signal SRA (only 0.5A) was much lower than that one in the power SRAs (up to 7.5 A).

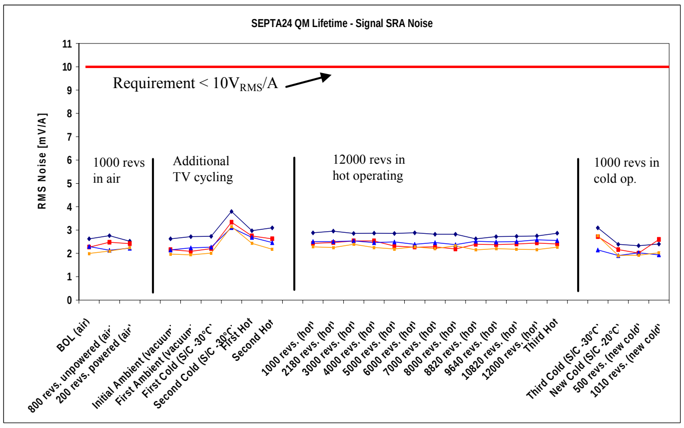

Figure 14: Signal SRA Noise (RMS Values) Evolution during Lifetime

Finally, the accuracy and the electrical noise of the potentiometers did not change during the lifetime confirm the excellent measurements obtained from the functional tests performed after vibration and shock tests as well as during the TV tests.

6.2. Motor Margin Evolution

The motor margin verification tests performed during the lifetime test basically consisted of measurement of the minimum current at which no step losses were detected among a full output revolution.

In fact, since the repeatability of the reset switch is better than 0.01 deg – which correspond to less than two motor steps at input shaft – the step loss was detected when the reset switch did not activate after step commands corresponding to a full output revolution.
Therefore, per each thermal case, the following measurements were performed:

- Minimum current at which no step loss (i.e. successful activation of the reset switch) was detected;
- Nominal current corresponding to the nominal voltage provided by the SADE to the motor coils.

The minimum torque as well as the nominal torque was derived from the current measurements knowing the motor constant at different motor coil temperatures.
By calculating the corresponding motor margin, a slight correction factor was introduced in order to take into account the inertia effects of the SA wing in the real operation in orbit. Nevertheless, it was demonstrated that these effects are negligible compared to the resistive torque in the SADA due to the high gear ratio used.

The findings observed during the lifetime can be summarized as following:

- During the additional TV cycling before the hot cycles the motor margins measured during the first TV cycling were confirmed. At ambient motor margins of about 4.4 were observed, whereas in hot and in cold the margins are about 3.2. This difference is likely to be due to a combined effect of higher resistive torques in the bearings and gearbox in the cold case and less driving torque available in the hot case.
- During the 12000 hot operating cycles, the motor margin remained constant at a value of 3.2.
- After the 12000 hot operating cycles, the motor margin in the cold case dropped below three. An extensive motor margin investigation was carried out in different cold conditions at different the I/F temperatures as well as with and without SRA power transfer. From these motor margin tests it transpired that when the temperature of the input shaft bearings was below 5-10 deg the motor margin dropped below the minimum required.
- During the last 1000 cold operating cycles, an increase of the motor margin was observed. Nevertheless, the motor margin was still below three.
- After the 1000 cold operating cycles, an additional motor margin investigation was carried out in different cold conditions as during the first investigation. The findings observed during the first investigation were confirmed so far. In the ambient and hot cases motor margins were exactly as at BOL, whereas in the cold case they dropped below three when the temperature of the input shaft bearings was below 5-10 deg.
- During the last ambient case and during the functional tests in air after lifetime the motor margins recovered to the initial values observed at BOL.

During the disassembling of the mechanism from the TV chamber, TV test setup was inspected carefully to check if clashes could be occurred between the fixed and rotating parts of the setup. No scratch or damage was detected during the disassembly of the TV test setup.

A partial strip down was carried out on the QM. The so far visible areas of the actuator show liquid lubricant still present at all rolling interfaces.

Further motor margin tests were performed in vacuum on the partially stripped QM (without slip rings and front bearing, i.e. without resistive torques on the output shaft).
Based on the findings of all these investigation, it can be concluded that the decrease of the motor margins in the cold cases is likely to be due to increase of the resistive torques at the input shaft. This might be related to one or both following reasons:

- Grease migrated from the gearbox to the small gap between input rotor shaft and fixed parts partially during assembly and partially due to gravity effects;
- Limitation of the lubricant system used in the bearings and gearbox in cold conditions due to the fact that micro-wear might increase the viscosity of the grease at cold temperatures.

The final strip down activities are expected to be completed by end of July 2011.

7. SUMMARY AND CONCLUSION

The full SEPTA®24 qualification programme has been presented in this paper. The results of the development tests on the critical components of the SRA showed the suitability of the SRA design features as well as of the materials used for applications of the slip rings in severe thermal and mechanical environment such as geostationary applications. The findings of these development tests are useful not only for the SEPTA®24 applications but also for other application where high temperature requirements are demanded.

The SEPTA®24 QM showed excellent electrical as well as mechanical performances after vibration and shock tests as well as during the TV cycling.

The lifetime has been also completed. The electrical performances of slip rings and potentiometers did not change significantly and remained well within the specified requirement throughout the lifetime test.

Finally, the motor margins remained constant throughout the lifetime in the hot operating and ambient cases. A decrease in cold case occurred after 12000 hot operating cycles, which has been extensively investigated after the hot operating cycles as well as after the cold operating cycles and on the partially stripped QM. These torque margin drop-off is likely to be due to an increase of the resistive torques at input shaft.

It can be concluded that the qualification test campaign on the SEPTA®24 QM has been successfully completed including the lifetime test, pending completion of the investigations to be carried out as part of the final QM strip down.

8. ACKNOWLEDGEMENTS

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