Development of Brushed and Brushless DC Motors for use in the ExoMars Drilling and Sampling Mechanism

Robin Phillips*, Massimo Palladino** and Camille Courtois+

Abstract

This paper presents a summary of work performed to qualify two COTS (Commercial Off The Shelf) motor types (one Ø13 mm brushed and one Ø22 mm brushless) for operation in a Martian atmosphere for the ExoMars Drilling and Sampling Mechanism. We present all the major steps in this process, which included an analysis of features that needed changing from the standard industrial motor design, a development program that was undertaken to select an appropriate design, and a qualification campaign that was then applied to the modified motors.

Introduction

Maxon motor is well known for having built all the drive and steering motors for JPL's Mars Pathfinder (Sojourner) and MER (Spirit & Opportunity) rovers where the soundness of the basic design has been demonstrated over the 7+ years that Opportunity has now spent roving on the Martian surface.

Maxon was also selected by ESA to develop motors for its ExoMars rover mission. However, the significant differences in requirements for the Drilling and Sampling mechanism did not allow the selection of the same type of motors as MER used. Specifically, the specified lifetime and power output for the main drill drive motor required the use of a brushless motor since the expected lifetime of a brushed motor was not sufficient for this application. Additionally, space restrictions inside the drill required the use of a smaller brushed motor (Ø13 mm) than had been used in either of the previous JPL missions.

As with the JPL RE25 development, the aim was to adapt industrial standard motors (i.e., a so called "Commercial Off The Shelf" or COTS design) rather than to develop a custom solution in order to lower development costs. The process followed in the development program included three main steps:

1. A detailed analysis of the standard industrial motor design to identify features that were unlikely to work correctly when exposed to the environmental conditions and duty cycles requirements of the ExoMars mission.
2. Research into possible solutions to the identified design problems and then an appropriate redesign of the motors.
3. Manufacture and qualification testing to simulate all relevant aspects of the ExoMars mission on the new design.

Mars Rover Electric Motors Background

Successful operation of electric motors on the Martian surface was initiated by the Viking project which put two landers on Mars in 1976. The Viking landers used numerous motors in the twin cameras (e.g., for rotating the camera housing and moving the scanning mirror) as well as for the sampling boom and communications antenna pointing. That electric motors have a history of causing technical difficulties for

---

* maxon motor ag, Sachseln, Switzerland

** ESA, ESTEC, Noordwijk, The Netherlands

+ RUAG Space, Nyon, Switzerland

Proceedings of the 41st Aerospace Mechanisms Symposium, Jet Propulsion Laboratory, May 16-18, 2012

Martian applications is revealed by the appearance of the “Surface-sampler boom motor” in the list of “Top Ten Problems” for the Viking development program between Feb 1973 and Sept 1974 (Ezell and Ezell 1984, p. 253).

After Viking there was a long pause until the Mars Pathfinder landed with the small Sojourner rover in 1997 which contained 11 maxon RE16 brushed motors. The Sojourner rover covered about 100 m before the lander communication link failed, thereby ending the mission after nearly 3 months. In covering the 100 m in just under 3 hours of driving time the drive motors rotated approximately 0.5 million times (with another 0.5 million during Earth based testing) with no indication of motor problems (Braun 1998).

Following the success of the Mars Pathfinder mission, two larger and much more capable rovers were flown on the Mars Exploration Rover (MER) missions that landed the rovers Spirit and Opportunity on Mars in 2003. Each rover contained 39 maxon motors for drive and steering functions, solar array deployment, camera mast actuators and the actuators for the science arm joints. Two different motor types were used, a modified RE25 as can be found in maxon’s standard program and a RE20 that was specially developed for the MER program. The success of these missions is well known and as of January 2012 Opportunity was still active and had driven nearly 35 km over the previous 8 years.

For the follow on MSL mission (launched in 2011), due to the increased distances the rover was expected to cover, brushless motors were selected. The development of these motors and associated gearboxes proved much more complex than expected and, as has been well documented in the press, ultimately led to a two year delay in the launch, emphasizing again the complexity involved in specialist motor design.

Selection of Motor Types for the ExoMars Application

The ExoMars program (as originally conceived by ESA) envisaged many motors of numerous types being used for various different functions on the rover, a summary of which is shown in Table 1. For the purposes of the development program being reported on here, the requirements for the Drilling and Sampling mechanism, hereafter “Drill”, were considered. Where possible the RE20 and RE25 brushed motors that were used on the MER missions were used in the original design. However, three applications in the drill required new motor sizes or types. These were the Drill mandrel clamp which has to fit within the diameter of the drill bit (see Figure 1) and hence is limited to Ø13 mm, the main drill drive

Table 1: List of motor applications on the ExoMars rover

Function	Motor type	Quantity on rover
Wheel Drive	RE 20-25	6
Steering Drive	RE 20-25	6
Deployment Drive	RE 20-25	6
Camera Mast Pan Axis	RE 20-25	1
Camera Mast Tilt Axis	RE 20-25	1
Drill Positioner Translation	RE 20-25	1
Drill Positioner Rotation	RE 20-25	1
Drill Positioner Jettison	RE 20-25	1
Drill Translation	EC22long	1
Drill Rod Mag Rotation	RE 20-25	1
Drill Rod Mag Clamp	RE 20-25	1
Drill Rod Lower Clamp	RE 20-25	1
Drill Mandrel (main drive)	EC40	1
Drill Mandrel Clamp	RE13	1
Drill Tool	RE13	1
SPDS=Sample Preparation & Distribution System		

Function	Motor type	Quantity on rover
SPDS CSTM	RE 20-25	1
SPDS BSD	RE 20-25	1
SPDS Jaw actuation	EC22	1
SPDS De-block actuation	RE 20-25	1
SPDS Position/Rotary Motion	RE 20-25	1
SPDS Dosing Mechanism	RE 20-25	2
SPDS Carousel	RE 20-25	1
Solar Array Deployment	RE 20-25	1
Battery Isolation Switch	RE13?	2
Life Marker Chip (LMC) Instrument Inlet Valve	EC14fl	4
LMC Bellows pump	EC8	4
LMC Rotary Valve	RE13	4
Mars Organic Molecule Analysis (MOMA) Instrument	RE10	2

motor which due to the required lifetime and power requirements need to be a Ø40-mm brushless motor and the drill translation unit which due to power requirements was best achieved with a Ø22-mm brushless motor.

In order to avoid the motor problems that plagued the MSL development, a program was started to design and qualify both of these two new motor types. This program also had the express goal of making sure that the technology needed for making such motors was available outside of the USA so as to be free of ITAR restrictions. The first stage of this program was to analyze the existing commercial motor designs for features that were unlikely to be compatible with the ExoMars environmental and operating specifications.

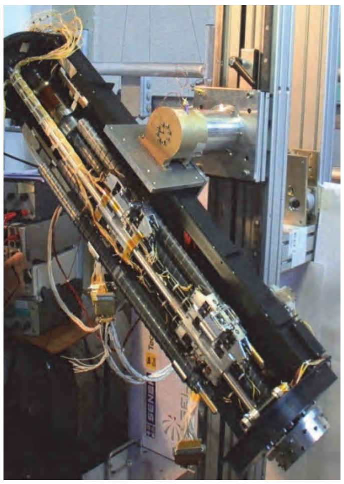



Figure 1: The ExoMars drill box breadboard (left) and drill mandrel EM (right)

Specifications Summary

Although much of the specification for the motors is similar to that for a terrestrial application, there are a few key areas that a significantly outside of the normal application regime that a COTS motor would be expected to be designed for, these are summarized in Table 2.

Table 2: Summary of ExoMars specification that is significantly different to an industrial standard application

Non-operating temperature range	-120 °C to 125 °C
Operating temperature range	-55 °C to 30 °C
Operating atmospheric conditions	1 bar, Earth standard 5-10 mbar CO_2 (Martian atmosphere)
Vibration environment	Sine 100 Hz, 33 g Random 20-2000 Hz, 17.2 g_{rms}
Shock loading	100 Hz: 25 g , 300 Hz: 400 g 2 kHz – 10 kHz: 1500 g

Several features of both motors that were incompatible with these specifications had common solutions, such as modifying the bearing grease to Braycote 601EF for the low temperature pressure environment and changing the wiring to a type compatible with standard ESA wiring specifications. Various materials in the standard motor designs were modified, such as the aluminium housing and front flange of the EC22 which were changed to titanium, in order to avoid problems with differential expansion (aluminium bearing seat to stainless steel bearing race for example) or to reduce the mass. Other features, however, were specific to each motor type and are described in more detail in the next two sections.

Key Problems for Brushed Motors

Derating factor

The RE13 standard motor has a specification sheet defining the maximum mechanical output power (i.e., torque and speed) allowed. The extremes of the continuous operating regime are determined by the maximum allowed winding temperatures (125 °C in the case of the RE13). Normally the winding will cool via a mixture of conduction (via the shaft), convection (via the air surrounding the winding) and radiation. A reduction of atmospheric pressure will cause a corresponding reduction in the convection component of this cooling and hence in the available performance from the motor.

In order to quantify the size of this effect, a simple test was conducted with an RE13 motor in a vacuum chamber. The resultant measured thermal resistances (Table 3) could then the programmed into maxon's standard motor simulation software and new maximum continuous torque calculated. As can be seen from Table 3, the presence of even a small atmosphere causes a dramatic improvement in thermal conductivity.

Table 3: Measured winding to housing thermal resistance and corresponding maximum continuous torques for RE13

Atmospheric pressure (all with Earth standard composition)	Thermal Resistance (Winding->Housing) [K/W]	Maximum continuous torque [mN-m]
1 bar	7	2.39
7±1 mbar	9	1.85
$<1x10^{-3}$ mbar	50	0.811

Vibration and Shock Considerations for Brushed Motors

For the RE13 motor, there was concern that during shock and vibrations (mainly from launch and landing) there is no contact between the motor winding and the housing. This is particularly of concern since the RE13 motor winding is a cantilever (Figure 2) and the gap between the winding and housing can in the worst case tolerances be only 170 µm, as shown in (Figure 3).

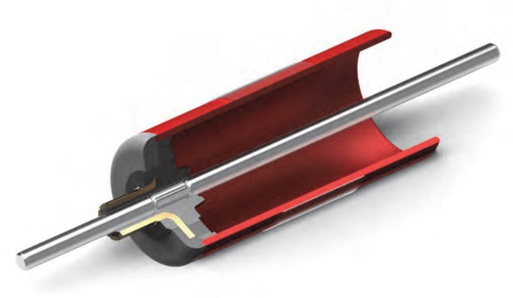


Figure 2: RE13 rotor showing bell shaped winding attached to shaft

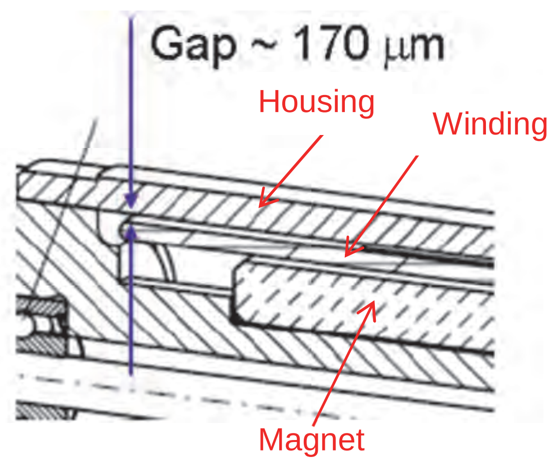


Figure 3: Detail of gap between RE13 winding and housing

Based on a resonance search performed on the rotor by itself (see Figure 4), the winding fundamental frequency and the associated amplification factor were found to be 529 Hz and 3.5 respectively. Considering the random vibration requirement, by using the Miles equation for displacements, the winding displacement is given by:

$$dispRMS = \sqrt{\frac{PSD(fres)Q}{32\pi^3 fres^3}}$$

where *fres* is the motor winding fundamental frequency, Q is the amplification factor at resonance, PSD(*fres*) is the specified power spectral density of acceleration at frequency f and *disp*RMS is the RMS displacement. The motor winding RMS displacement during random vibration was found to be 25 µm with a 3 sigma peak of 75 µm. Therefore, any contact between the motor winding and the housing is excluded, even at 3 sigma (since the gap is no less than 170 µm). A random vibration test was performed on the fully assembled RE13 as part of the qualification testing and no signs of contact between winding and housing were seen after the test.

A shock analysis was performed to assess the behavior of the RE13 motor winding, considering the required shock response spectrum. A half-sine shock of 1500 g amplitude and 0.5 ms was applied. Figure 5 shows that the shock generated (in red) envelopes the required shock response spectrum (in dotted blue).

Figure 4: Test setup for the random vibration test conducted on the RE13 winding

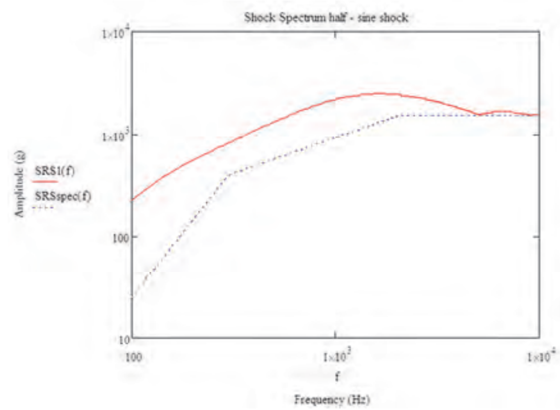


Figure 5: Shock response spectrum applied on the motors

The displacement of the motor winding during shock, evaluated by analysis, is about 1 mm. This shows that the contact is likely. However, the shock will only create a contact between the motor winding and the housing during a very short period of time. This is considered acceptable (the time is short enough to avoid any damage). The shock test performed on the assembled RE13 motor showed that indeed no effects from such contact were observable.

Brush material

Although brushed motors have the advantage of not needing complex commutation electronics, they determine the lifetime of the motors and cause the life to be much lower than for an equivalent brushless motor. Unfortunately the most common brush materials for high current applications used in industrial motors (copper or silver graphite mixtures) require the presence of water vapor and oxygen to build up a hardened patina on the wear surface of the brush. If the water vapor is not present, then extremely rapid wear can occur.

The situation with no water vapor applies on Mars and was noticed during qualification testing for the Viking lander camera scan mirror motors in the mid 1970's (Mutch 1978, p. 17). Twenty years later for the Sojourner rover the problem was circumvented by the use of precious metal brushes without lubrication in otherwise nearly standard RE-16 motors. This is a simple solution for situations where required torques are low and only limited lifetimes are required. Testing for Sojourner showed that under load and start-stop conditions motor failure occurred after about 30-40 million revolutions (Braun 1998) which was more than sufficient for the planned mission.

For the MER mission a more extensive testing program was undertaken to test various different brush materials. Some of the early testing has been described in detail in (D. E. Noon 1999) and (Reid, Braun and Noon 1999), and it consisted of testing motors from various manufacturers with brushes made of mixtures of copper or silver graphite with impregnation with various different lubricants. For the flight models, the RE20 was flown with a copper graphite brush with 8% MoS_2 content (from Le Carbone) whereas the RE25 was flown with silver graphite brushes and 5% MoS_2 content (from Shunk). The success of these rovers (and by implication the motor and brush choice) has been well documented in the general press. Although the motors have not been completely trouble free (e.g., one failed drive motor on Spirit and one drive motor with periodic increased current draw on Opportunity), they have worked well enough to allow, in particular the Opportunity mission to significantly surpass the expected distance covered. The ~35 km driven by Jan 2012 represents ~65 million motor revolutions. This is well within the estimated lifetimes of several hundred million revolutions obtained from testing – although it is worth noting that the testing demonstrated a very large scatter with the (D. Noon 2001) report stating that the life could be as low as 10 million revolutions, which was indeed the case for Spirit's failed motor.

It is clear from the published reports that the selection of the correct brush material is critical to obtaining good lifetimes. Unfortunately explanations as to why significantly different brush mixtures were chosen for the RE20 than for the RE25 motors are not available in the published literature. What has been published shows a wide variation in the performance of similar brush materials with differing motor loads. Given that insufficient understanding of these issues was available either within maxon or ESA, it was decided to undertake a new test program for the RE13 motors.

Table 4: Brush breakage test results showing values (in newtons) where the brushes failed. It is coincidence that types 1-3 have exactly the same mean and standard deviation.

No.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7
Mean	9.5	9.5	9.5	10.8	9.1	7.2	5.9
SD	1.0	1.0	1.0	1.1	0.6	0.8	1.3

For the test, 24 RE13 motors based on type 118626 were used. Differences to the standard motor were the inclusion of Braycote 601EF lubricated bearings, a fiberglass re-enforced winding, an extended length shaft, and the various brush materials to be tested. The brush materials shown in Table 5 were tested, in each case three motors were built

It is of course not only important that the brushes have a long lifetime in use, but that they also are structurally strong enough to withstand launch vibrations and shocks. A simple mechanical strength test was undertaken using a standard maxon procedure that is used to quality control standard brush lots. The brush is attached to a holder through its normal mounting hole, a rod is placed into the brush hook and force applied to pull on the brush arm. The force needed to break the arm off is shown in Table 5 where it can be seen that for the copper-based brushes there is no difference in strength. For silver-based brushes, increasing amounts of MoS_2 weaken the brush. However, the effect is probably not large enough to cause a problem; for comparison the maxon standard material (type 8 in Table 5) is specified to withstand a force of 8 N, other standard materials have specified values as low as 4 N.

The brushes were constructed using the same mold as for the standard RE13, with a contact cross sectional area of 2.4 mm^2. Standard springs were also used that yield a contact force of 12.5 $N\text{-}cm^{-2}$ with new brushes (as the brushes wear, the force reduces as the spring uncoils).

The motors for the ExoMars application are required to operate for testing and qualification on Earth in a standard Earth atmosphere as well as for short periods in vacuum while travelling to Mars and of course extended operation on Mars in a 5-10 mbar CO_2 atmosphere. Hence the test program was specified with the segments as shown in Table 6. The motors were to be operated at the maximum working point defined by the specifications of 2.3 mNm load at a rotation speed of 8000 rpm.

Table 5: Brush material types tested. Motor group number is used elsewhere in this report to refer to a particular brush material type. Group 7 with a very high silver content was an attempt to produce a brush that was optimized for vacuum operation.

Motor Group	Brush Material
1	50% Cu 45% C 5% MoS_2
2	50% Cu 40% C 10% MoS_2
3	50% Cu 35% C 15% MoS_2
4	50% Ag 45% C 5% MoS_2
5	50% Ag 40% C 10% MoS_2
6	50% Ag 35% C 15% MoS_2
7	85% Ag 3% C 12% MoS_2
8	50% Cu 50% C

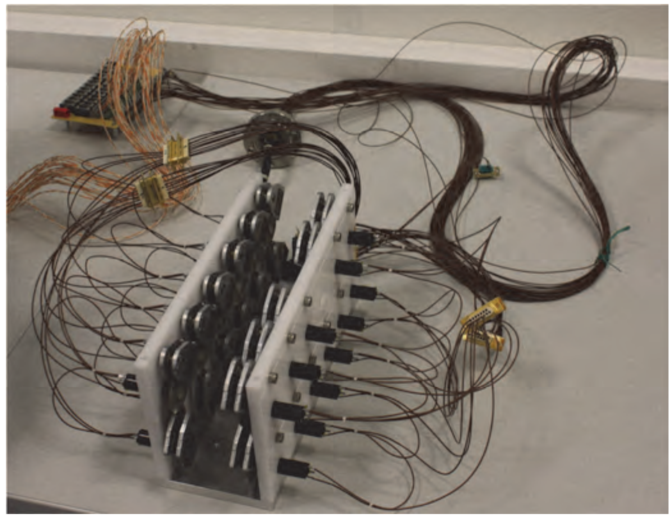


Figure 6: Motor holder setup. The eddy current brake magnets are visible on the inside.

Table 6: The test sequence followed. The motor revolutions column shows the approximate number of revolutions the motors made during each test phase (based on actual number of hours run and the approximate speed settings).

Period	Gas	Pressure	No. of motor revolutions
3 days	78% N_2, 21% O_2 + other traces	~1000mbar	30 million
2 weeks	CO_2	5-10mbar	165 million
1 week	none	$<10^{-6}$mbar	60 million

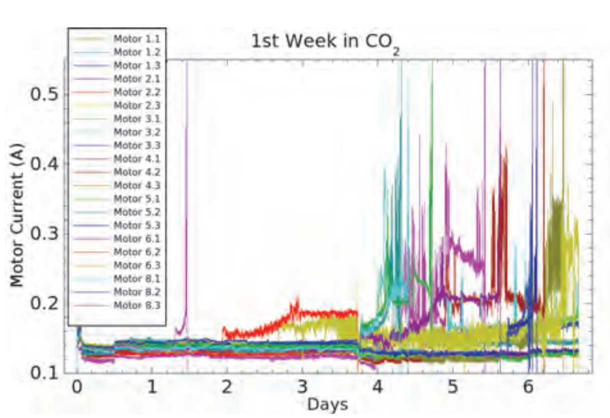


Figure 7: Current draw for all motors in 8 mbar CO_2 test.

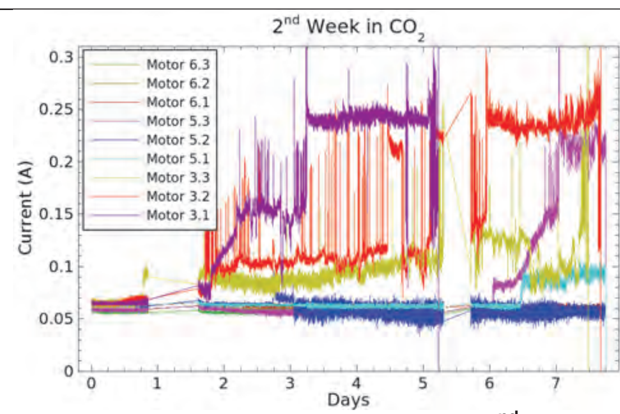


Figure 8: Motor currents during the 2nd week in 8 mbar CO_2 atmosphere. The gaps in the data are caused by the logging PC crashing - the motors continued to run in these gaps.

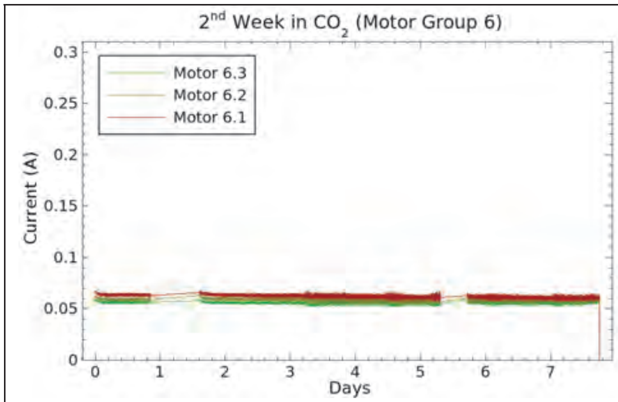


Figure 9: Motor current from the best performing brush types where no deterioration is seen after two weeks near continuous operation.

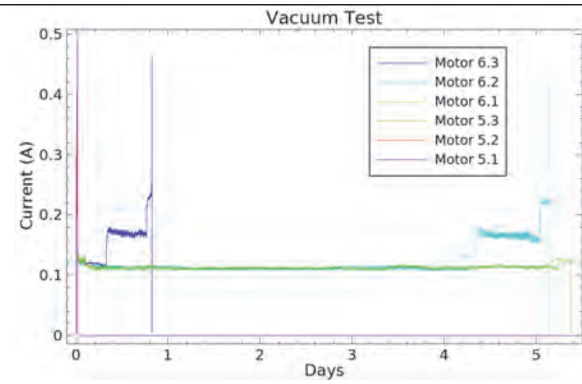


Figure 10: Motor currents during operation in vacuum. Brush type 5 all failed within 25 minutes of starting the test!

In order to simulate a near worst-case thermal situation, the motors were mounted in a plastic Polyoxymethylene (POM) holder (see Figure 6) so there would be minimal thermal conductivity. Eddy-current brake disks were used to provide the required load. Each motor was individually monitored and its current draw logged.

At the end of each test phase, 2 of the 3 motors with a particular brush type were opened up and pictures of the brushes and collectors taken under a microscope. The 3rd motors of each brush type were not opened so as to retain the worn material inside the motors. The motors that were opened had all loose brush material vacuumed out before re-assembly. Other than vacuuming, no attempt to clean them was made; in particular the collector slots were not cleaned (other than vacuuming).

The initial 2.5-day run under normal Earth atmospheric conditions produced the main result that the group 7 motors all failed within the first 14 hours. Inspection of these brushes showed that the cause of failure was the complete wear of the brushes. Thus these brushes are shown to be unsuitable. The following one week of operation in an 8 mbar CO_2 atmosphere was performed with the motors operating with loads of between 1.65 mN-m and 2.05 mN-m and speeds of between 8500 rpm and 9200 rpm. The differences were caused by a mixture of motor manufacturing tolerances (all motors shared the same power supply) and variations in how the eddy current brakes responded variably to running in a vacuum after being set under atmospheric conditions (brake adjustment after being placed in the vacuum chamber was not possible).

The first week of operation in an 8 mbar CO_2 atmosphere also produced a number of failed motors. The first motor (equipped with maxon standard brushes) failed after 1.5 days followed a few days later by additional motors. By day 6, all group 8 motors (standard brushes), all group 1 motors, all group 2 motors, and 2 of 3 group 4 motors had failed. These were the groups with lower MoS_2 content. Additionally, all group 3 (Cu 15% MoS_2 brushes) showed increase current draw. We therefore decided to interrupt the test and open all failed motors to inspect the brushes.

It immediately became clear upon inspecting the brushes that the motors were failing due to the complete wear of the brushes. As the brushes come to the end of their life, the section in contact with the collectors becomes wider causing several collectors to be in contact with the brush at the same time. This leads to winding segments being short circuited and hence a higher current draw.

One problem that had not been anticipated was that as the motors start to fail they dramatically heat up. In the case of motor 8.2, which had a temperature sensor on it, the housing reached over 180°C (implying a winding temperature of >200°C!). This caused the POM support structure to melt and hence their brake disks to contact the brake magnets. Thus no significance can be attributed to the presence or variation of spikes and other features in the current curves once the motors start to fail.

The major results of this first week of testing are that copper-based brushes do not work as well as silver-based brushes for high load situations like this, and that in both material types more MoS_2 results in slower wear rates.

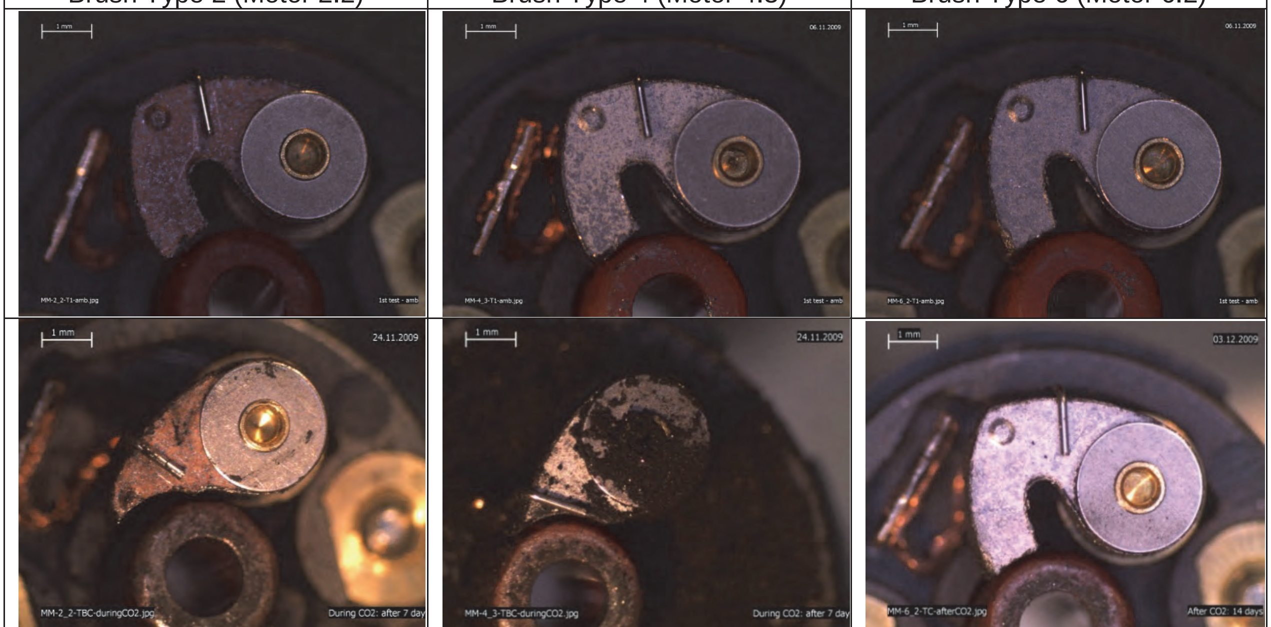
Brush Type 2 (Motor 2.2)	Brush Type 4 (Motor 4.3)	Brush Type 6 (Motor 6.2)
		
After 1 week CO_2	After 1 week CO_2	After 2 weeks CO_2

Figure 11: Pictures of the RE13 brushes after 1 week operation in Earth atmospheric conditions (top row) and 1 week operation (2 weeks for type 6) in an 8 mbar CO_2 atmosphere (bottom row).

Since the results from the first week of tests were now understood, we decided to run the second half of the CO_2 test at a lower voltage to test a different working point. The eddy current brakes were set to a value corresponding to a load of 0.65-0.8 mN-m at 8000 rpm. Since the ExoMars specification of 2.3 mN-m includes all possible margins, actual operation would be expected at a lower power setting so it is also important to test at these lower current settings.

The results from the second week of CO_2 testing clearly re-enforce the results of the first week. The silver-based brushes work considerably better than the copper-based brushes and the higher the quantity of MoS_2, the longer the brush lasts. No significant wear is present in group 6 brushes, even after 2 weeks of operation (see Figure 9). It seems likely that some significance can be attributed to the result that both motors 3.3 and 5.3 (i.e. those which were not opened and hence retained the worn brush dust) started to fail before those motors which were opened and cleaned, however the effect is not large.

The results from the vacuum testing were consistent with what was been reported by (D. E. Noon 1999) in that failure is extremely rapid and is caused by brush wear residue accumulating between the collector bars and causing partial shorts. Type 5 motors were already starting to wear out at the end of the CO_2 testing as they were showing increased current draw. Despite this, we were surprised at how fast they failed; after less than half an hour of running in vacuum all three group 5 motors had failed.

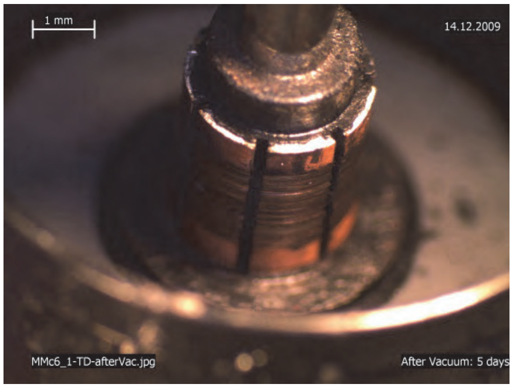


Figure 12: Type 6 collector after the final vacuum test - wear levels are very low, however the collector bars are partly shorted together by material stuck between them.

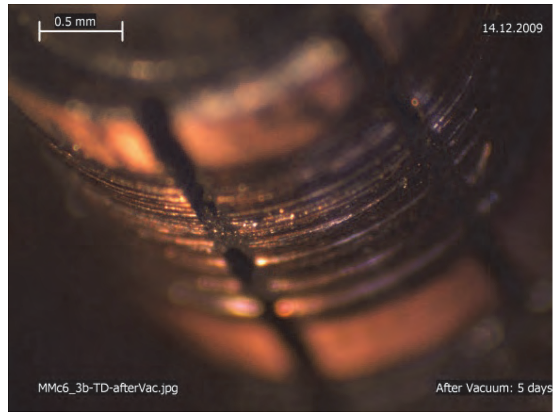


Figure 13: Example from type 5 brush where material can be seen shorting the collector bars.

Key Problems for Brushless Motors

For the BrushLess DC (BLDC) motors, the brush wear problem of course is not present. However, commutation for a BLDC motor needs a feedback device to tell the control electronics when to commutate (sensorless operation using back-EMF rather than a physical feedback device is not suitable for start stop operation or where high loads can be expected on startup). The most common way of performing this feedback is using hall sensors; however these are vulnerable to radiation damage. The ExoMars mission specifies a total dose threshold of 10 krad, defined as the end of life dose deposited under 2 mm of Al-eq solid sphere shielding with a safety factor of 2. In order to provide additional safety margins, the motor is specified with redundant hall sensors, each set being capable of operating the motor alone. Although a number of radiation hard hall sensors are available, these suffer from the major problem that they are US sourced and hence covered by ITAR. Additionally the sensors that we were aware of are all larger than ideal for a Ø22-mm motor. We therefore decided to test several non-US sourced sensors that maxon uses in various motor lines to see if a standard type could be used.

Figure 14 shows the test setup where 3 examples of each type of hall sensor to be tested, mounted on a PCB, were placed in front of a rotating permanent magnet. During the test, the sensors were in continuous operation. The permanent magnets were rotated using standard RE13 and RE25 motors, thereby simultaneously confirming that the radiation caused no problems for the two main types of brushed motors to be used (no effects were expected and none were seen). The radiation dose was delivered over a period of 90 hours at a rate of 0.079 Gy/min, yielding a total dose of 38 krad (Si). The sensors were additionally retested after an annealing period of 100 hours (at 25°C) to confirm no further changes.

Table 7 shows that only the Infineon TLE4945 sensor passed the test with no measurable degradation of the switching level. This result is not unexpected since the Infineon sensor is of bipolar design whereas the others are CMOS which is known to be more sensitive to radiation. Subsequent low temperature testing of the Infineon sensors was undertaken to ensure their operation at -55°C (the manufacturer only rates them to -40°C). With the successful passing of this test, these sensors were selected for design into the EC22 motors.

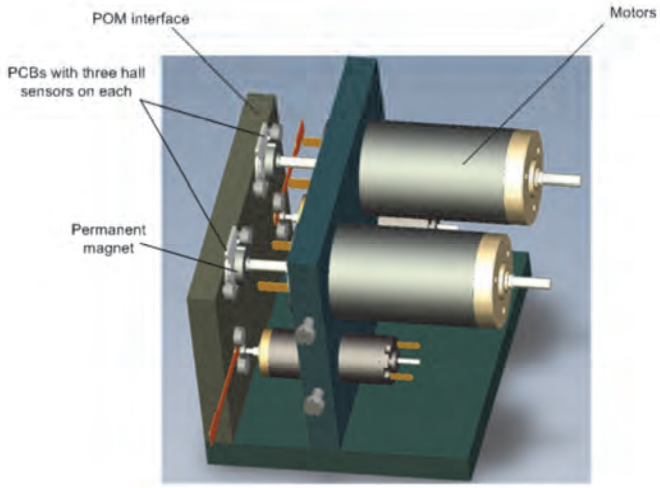


Figure 14: Test setup for hall sensor irradiation with test configuration of 4 PCBs, each with 3 hall sensors of one type, mounted in front of four motors with permanent magnets attached to their output shafts.

Table 7: Results of Hall sensor irradiation

Sensor type	Behavior during irradiation	Switching level after annealing
Melexis US3881LSE	Output voltage started dropping after ~20 krad	2.2 V
Melexis US4881LUC	Output voltage started dropping after ~20 krad	0 V
Infineon TLE4945	No change observed	5 V
Allegro A3230	No change observed	0 V

Qualification Testing

In order to qualify the motors for operation on Mars, a test sequence was established to fully test all phases of a motor's life, including ground testing, launch, travel to Mars and of course operation on the Martian surface. The major steps of the test sequence are shown in Figure 15.

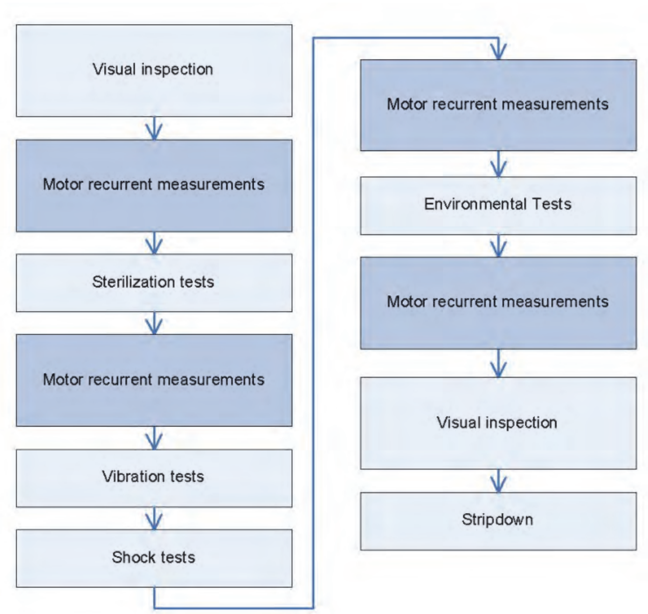


Figure 15: Motor qualification test sequence

Table 8: Shock requirements for ExoMars mission

	Shock Response (Q=10)	
Frequency	Launch from Earth	Landing on Mars
100 Hz	25 g	10 g
300 Hz	400 g	30 g
2,000 Hz	1500 g	30 g
10,000 Hz	1500 g	30 g

The "motor recurrent measurements" shown in Figure 15 was a defined sequence of measurements, including winding resistance, dielectric strength and inductance, housing capacitance and motor torque constant that was repeated after every major test step.

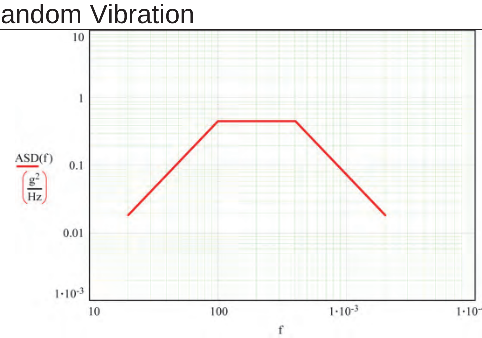
Sterilization tests

The ExoMars program has established a document describing the planetary protection requirements that applies to "all ExoMars spacecraft elements" (Kminek 2007). For the purposes of this qualification, a simple test consisting of 60 hours at 125°C in a dry N_2 atmosphere was considered adequate.

Shock Tests
The requirements for launch and landing shocks are given in Table 8. Only the launch levels were tested as shown in Figure 16.

Vibration Tests
An initial resonance search was performed consisting of a sine sweep with frequency 5-2000 Hz, sweep rate of 2 $^{oct}/_{min}$ ±5% with an amplitude of 0.5 g. Next, a sine sweep at the specified rate (2 $^{oct}/_{min}$ ±5%) and at the amplitude shown in Table 9 was performed for 2 minutes for each of the three axes. The motors were not operated during this test (reflecting the launch conditions). Finally, a random vibration test was run, also for 2 minutes per axis for all three axes.

Table 9: Vibration parameters for both RE13 and EC22 motor tests

Sine vibration		Random Vibration		
Input Freq.(Hz)	Amplitude	Input Freq. (Hz)	Amplitude	
0-20	15.5 mm peak	20-100	+6 [dB/oct.]	
20-100	27.2 g	100-400	0.45 [g^2/Hz]	
		400-2000	-6 [dB/oct.]	

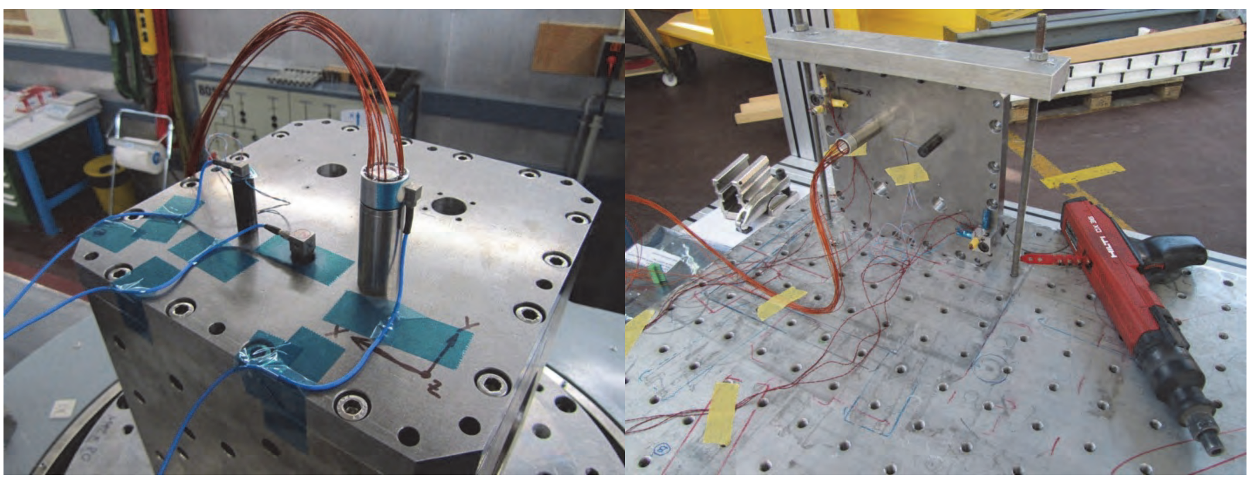


Figure 16: Picture of RE13 & EC22 test motors attached to a stiff mounting cube (note the feedback accelerometers attached to both motors in the left picture) on the shaker (left) and on a plate for the shock test (right). The powder actuated nail gun used to impart the shock is visible at the right.

Operating Cycles
The central part of the qualification tests for both motor types were low temperature, 8 mbar CO_2 and vacuum lifetime tests with representative loads were performed as shown in Table 11. In each case, the test setup consisted of a brake motor (whose braking load could be adjusted via a variable resistor across the windings) and the motor being tested as shown in Figure 17. A bearingless torque sensor was used to couple the two motors together and provide a reading of the actual braking force being applied. The speeds and loads used during the lifetime tests were the reference "worst case" loads given in the ExoMars specifications.

Table 10: CVCM per item

Temperature	RE13	EC22
-25°C	0.22 mg	0.57 mg
-50°C	0.37 mg	0.86 mg
-75°C	0.42 mg	0.92 mg

Table 11: Low temperature, CO_2 & vacuum tests

Motor	Test step	Temperature range	Load torque & rpm	No. of cycles	Approx. no. of motor revs.
EC22 RE13	Low temp. cycles	-120°C to +25°C	none	10 non-operating	0
EC22	Operating cycles	-55°C to 40°C	25Nm@12,000rpm	10x as in Figure 19	7.2 million
EC22	Lifetime test (8 mbar CO_2)		25Nm@12,000rpm	500x as in Figure 19	360 million
EC22	Vacuum test		25Nm@12,000rpm	10x as in Figure 19	7.2 million
RE13	Operating cycles		2.3mNm@8,000rpm	10x as in Figure 19	4.8 million
RE13	Lifetime test (8 mbar CO_2)		2.3mNm@8,000rpm	150+200 as in Figure 18	22.4 million
RE13	Vacuum test		2.3mNm@8,000rpm	3x as in Figure 19	1.4 million

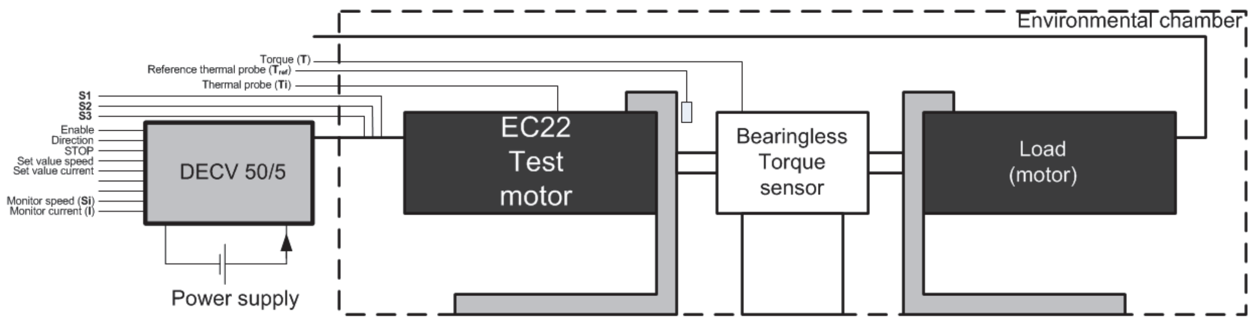


Figure 17: Test configuration for the EC22 (a similar configuration was used for the RE13)

<u>Outgassing performance</u>

To get a good performance from the motors in terms of particulates contamination and outgassing, which is essential for a mission like ExoMars that is searching for traces of life, the motors were baked out at 125°C for five days (the maximum allowable temperature of the windings). Following the qualification tests described above, the motors underwent outgassing tests at the ESA/ESTEC materials laboratory. The tests consisted of raising the temperature from 25°C to 125°C in steps of 25°C every 24 hours in a pressure of 10^{-7} mbar. The Collected Volatile Condensable Material (CVCM) and the Total Mass Loss (TML) were measured by using four Quartz Crystal Microbalance (QCM) plates at various temperatures as shown in Table 10.

Particulates emission from the brushes was a major concern for the RE13 motor since these are carbon based so several design features were added to make the exit path for wear particles from the motor as long as possible but to simultaneously ensure the minimum amount of material vents through the bearings during launch. However, the outgassing test results showed that there was negligible emission of particles from the brushes. The overall TML and CVCM levels were found to be very low.

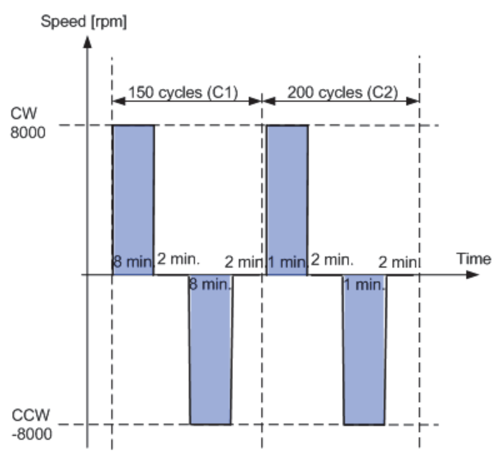


Figure 18: Reference cycle for RE13

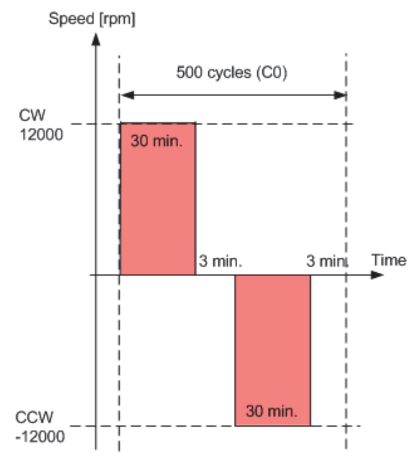


Figure 19: Reference cycle for EC22 (and certain RE13 tests)

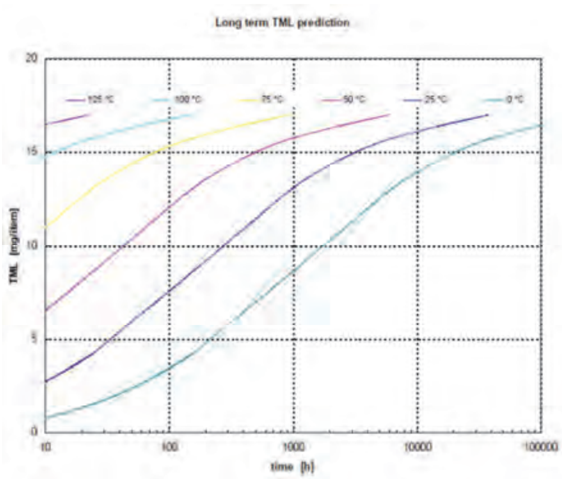


Figure 20: TML for RE13

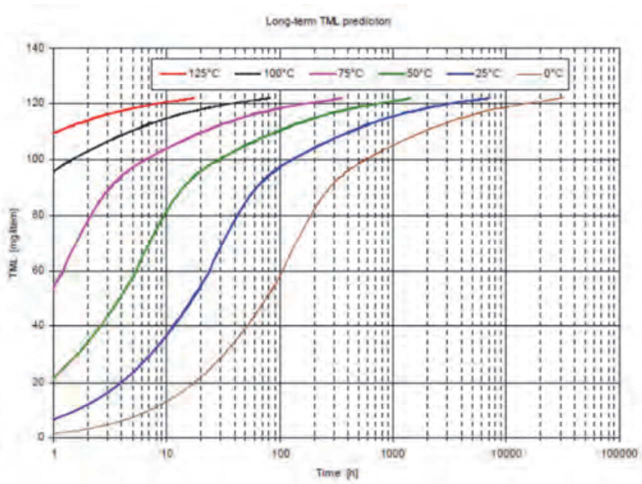


Figure 21: TML for EC22

For the RE13 and the EC22, the TML, measured at 125°C, is 17 $^{mg}/_{item}$ and 122 $^{mg}/_{item}$, respectively. Figures 20 and 21 show the TML extrapolated to different temperatures to predict more realistic operating scenarios. For the EC22, there was some concern related to an aromatic amine and a plasticizer. The TML and CVCM results showed that the aromatic amine and the plasticizer have been clearly removed by the bake-out. The low TML and CVCM levels measured for the RE13 and EC22 during the outgassing tests have resulted in a discussion within the ExoMars project as to whether the current requirement to encapsulate the motors can be dropped. This would save a significant amount of mass on the ExoMars mission, due to the considerable number of motors involved in the mission.

Qualification Results

Both motors passed the sterilization, vibration and shock tests with no noticeable problems (as determined by the recurrent measurements taken after each test step).

The RE13 performed without problems through the life test in CO_2. However, during the vacuum test, after just 2 cycles (representing just 2 hours operation), increasing current draw was observed and after the 3rd cycle the test was aborted to prevent damaging the motor and destroying any evidence of the cause of the problem. Upon strip down of the motor, it was clear that the cause of the problem was as had been seen in the previous brush wear tests and was caused by worn brush/collector material sticking between the collector bars and partially shorting the windings. No other major problems were seen during the strip down.

Although the EC22 completed all the life tests, including the vacuum part of the test sequence, two major problems were encountered. Most serious was the failure of two hall sensors after the “operating cycles” test listed in Table 11. In order to allow the sequence to proceed, the rest of the testing (including the main lifetime in CO_2 test) was performed using a sensorless controller (i.e., one that relies on back EMF to commutate). All the remaining hall sensors were still operational at the end of the test sequence. Upon strip down it was also noticed that the rear flange had worked loose (by about 0.5 mm) and had resulted in the partial failure of both bearings (due to extra forces on them since the rotor was no longer perfectly aligned to the stator. It is unlikely that the motor would have run for much longer in this condition.

Planned Future Work

Current work is concentrating on understanding the cause of the rear flange movement (for which a fairly simple mechanical design improvement is expected to provide a solution) and the more complex issue of why the hall sensors failed. So far, considerably more extreme temperature cycling on several additional PCBs has failed to reproduce the problem.

The next stage of the development program, which is expected to be performed during 2012, is to develop motor gearbox combinations using the motors described in this paper as well as the missing types listed in Table 1 that have not yet been qualified. This will also be an opportunity to confirm the effectiveness of the design changes to the EC22 to remove the two identified weaknesses.

Summary

The work presented here has shown that, with appropriate modifications, the COTS motors RE13 and EC22 are capable of standing up to the launch vibration and shock and a landing on Mars and then functioning for the full planned ExoMars mission in the environmental conditions found on Mars.

The necessity of a qualification campaign as described here is made clear by the failures that were encountered in the hall sensors and the weakness in the rear flange design of the EC22. With suitable modifications in these areas, we expect a trouble-free qualification of these motors when attached to the gearboxes for the next stage of development.

Acknowledgements

This work was performed in collaboration between maxon motor, RUAG Space and Selex-Galileo and was funded by an ESA development contract.

References

Braun, David and Noon, Don. *"Long Life" DC brush motor for use on the Mars Surveyor Program.* 32nd Aerospace Mechanisms Symposium, 1998.

Ezell, Edward C., and Linda N. Ezell. *On Mars: Exploration of the Red Planet 1958-1978.* Vols. SP-4212. NASA, 1984.

Kminek, G. *Planetary Protection Requirements.* ESA Doc. EXM-MS-RS-ESA-00005 Iss.3 Rev.1, 2007.

Kminek, G. *Planetary Protection Requirements.* ESA Doc. EXM-MS-RS-ESA-00005 Iss.3 Rev.1, 2007.

Mutch, Thomas A. *The Martian Landscape.* Vols. SP-425. NASA, 1978.

Noon, Don E. "Motor Brush Testing for Mars and Vacuum" *33rd Aerospace Mechanisms Symposium* 1999

Noon, Don. *Motor Brush Development Testing Results.* Unpublished, 2001.

Reid, Lisa K., David F. Braun, and Don E. Noon. "Robotic Arm and Rover Actuator Systems for Mars Exploration." *New Perspectives in Mechatronics Systems.* Winterthur, 1999.