Independent Review Support for Phoenix Mars Mission Robotic Arm Brush Motor Failure

March 8, 2007

NESC Request No. 06-050-E

Approval and Document Revision History

Approved:	Original signed on file	3-26-07
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
Base	Initial Release	NESC Discipline Expert, Mechanical Systems	03/08/07

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1.0 Authorization and Notification

The request to conduct an assessment on the Phoenix Mars Mission Robotic Arm (RA) Brush Motor Failure was submitted to the NASA Engineering and Safety Center (NESC) on August 10, 2006.

The authority to proceed was approved in an out-of-board action on August 10, 2006. Mr. John McManamen, NESC Discipline Expert (NDE) at Johnson Space Center (JSC), was requested to lead the review effort. The leadership responsibility was subsequently transitioned to Mr. Joe Pellicciotti, Mechanical System Chief Engineer at the Goddard Space Flight Center (GSFC) due to his expertise in similar systems.

An outbrief and final report was presented to the NESC Review Board (NRB) on March 8, 2007.

2.0 Signature Page

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3.0 Team List

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4.0 Executive Summary

The Phoenix Project requested the NASA Engineering and Safety Center (NESC) perform an independent peer review of the Robotic Arm (RA) Direct Current (DC) motor brush anomalies that originated during the Mars Exploration Rover (MER) Project and recurred during the Phoenix Project. The request was to evaluate the Phoenix Project investigation efforts and provide an independent risk assessment. This includes a recommendation for additional work and assessment of the flight worthiness of the RA DC motors.

The NESC IRT investigation was limited to teleconference and transfer of information electronically between the IRT and the Phoenix Project engineers. The information exchange process proved to be acceptable for the level of evaluation requested.

The RA motors (Figure 4.0-1) are of a single string brush DC type, which were originally built for the MER Project. The motor brush material (copper/graphite/MoS_2) was formulated by the Jet Propulsion Laboratory (JPL) and the brushes were manufactured in Europe by the suppliers to Maxon, the motor manufacturer (residing in Switzerland). The brushes were provided as Government-Furnished Equipment (GFE) to Maxon for producing the MER brush motors, replacing the stock brush material used for terrestrial applications. During the MER Project, the brush's sensitivity to external shock was demonstrated during the initial pyro shock qualification testing, which resulted in failure of the motor brushes. This was attributed to component shock testing that was subsequently determined to be an over test of the assembly. The motor design was eventually qualified for 2,600 Gs peak shock response spectra (SRS) during the MER Project. Since the pyro shock requirement for the Phoenix Project application was 1,500 Gs peak SRS, the motor design was deemed qualified by similarity and no component shock testing was performed. However, two motors were found during the Phoenix Project development to have broken brushes from unknown causes.

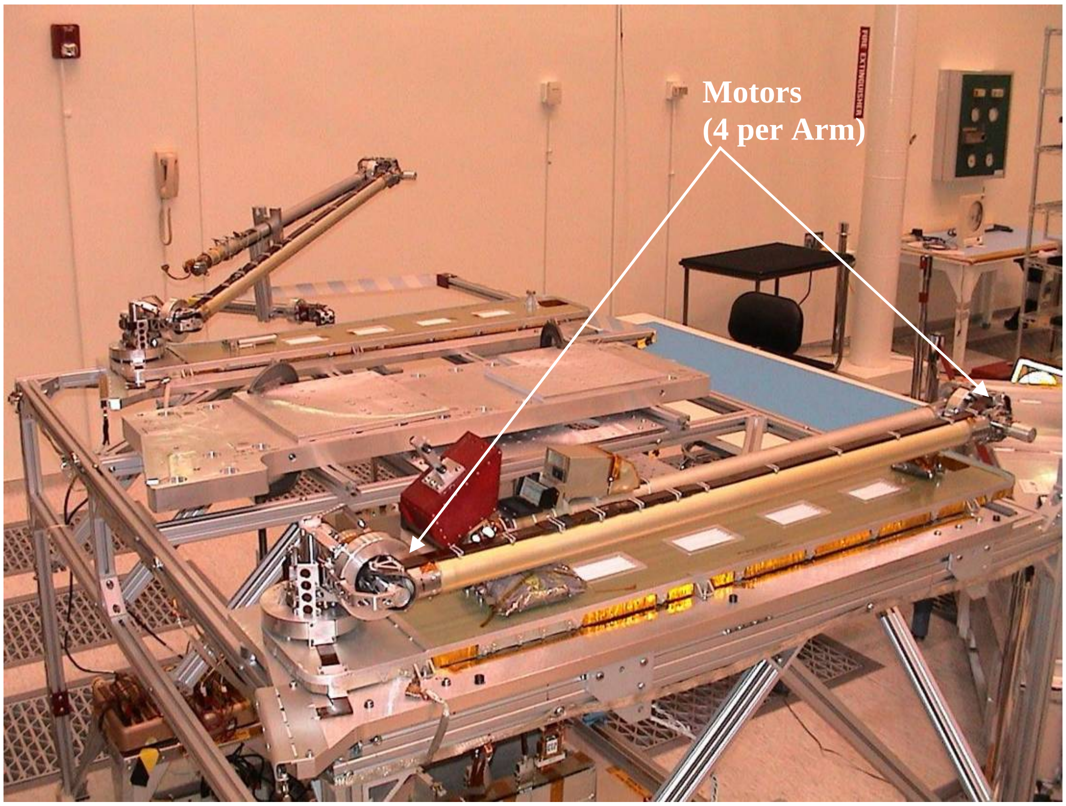


Figure 4.0-1. Flight Model (FM) and Engineering Model (EM) Phoenix Mission RAs

The Phoenix Project engineering group performed a detailed investigation into the anomalies that resulted in a Failure Cause/Corrective Action Rating of 4 (Unknown Cause, Uncertainty in Corrective Action), with a Failure Effect Rating of 3 (Major Degradation or Total Loss of Function). As of this report date, no 5x5 risk assessment was conducted by the project. These motors are critical to the Phoenix mission since a complete failure of a particular motor would result in meeting the minimum mission criteria or a loss of mission (LOM). The most likely cause of the brush anomaly was attributed to handling damage. This conclusion was drawn principally from a process of elimination of other potential causes and the fragility of the brushes to shock loading. There was no specific documented incident of a handling problem for the failed motors. However, the Phoenix Project did not have an explicit handling procedure, beyond best practices for handling flight hardware, to protect these motors from impact.

The NESC's Independent Review Team (IRT) assessment of project risk, using the standard 5x5 matrix, resulted in rating the risk in two separate areas of concern. The first is a brush pivot break with a consequence rating of 5 and a likelihood rating of 1. The second risk is for detection of a brush tip break with a consequence rating of 4 and a likelihood rating of 3. The rationale for these ratings are presented in Section 6.3 and based on the IRT evaluation of the motor screening tests and results.

The screening process for motor acceptability that the Phoenix Project implemented included detailed "motor health checks" (originally developed during execution of the MER Project). These checks involved standard static measurements such as motor resistance, insulation resistance, and dielectric breakdown as well as detailed examination of the high bandwidth current traces during initial operation. However, post environmental tests did not include the electrical "motor health checks" because of difficulties integrating the high resolution electrical equipment into the Phoenix Project Electrical Ground Support Equipment (EGSE). Only low resolution electrical measurements were performed. This rationale was deemed acceptable by the Phoenix Project because the high bandwidth "motor health checks" were specifically developed to detect internal open circuits in otherwise functional motors.

In addition to these electrical tests, an auditory test was developed for the Phoenix Project. Broken brushes generate debris in the motor housing. By manipulating the motors in different orientations while energized, the brush debris may move by the force of gravity and can contact the rotating armature, resulting in noise that can be audibly detected.

The investigation resulted in seven Findings, one Observation, and two Recommendation from the NESC Independent Review Team (IRT). The most notable of these is Finding (F-3) and the associated recommendation which discusses nondestructive inspection and neutron radiography (N-ray) testing. An N-ray test of the motors could be performed to evaluate the existing condition of the flight brushes while intact within the motor. Preliminary testing suggests that an N-ray test could reveal a macroscopic fracture (separation) of the brush material, although it is inconclusive that performing this test would reveal a crack in the brush.

Performing an N-ray test on the flight motors would provide a baseline configuration assessment where subsequent operations and handling could be controlled in a manner that limits loads on the motor. Having this inspection data post-environmental testing would provide confidence that the brushes have not been abusively handled, exposed to excessive shock loading, and/or are on the higher strength end (high scatter in brush strength testing) of the material lot, and therefore would reduce the risk associated with launch and operational failures (LOM). However, at this point in the project an inspection would require removal of the motors from the RA assembly. Once the RA has reached system level testing on the vehicle, removal of the motors for inspection is not recommended due to the potential for damage from the additional transportation and handling.

Based on the investigation and findings contained within this report, the IRT concurs with the risk assessment Failure Cause / Corrective Action (FC/CA) by the project, "Failure Effect Rating "3"; *Major Degradation or Total Loss of Function*, Failure Cause/Corrective Action Rating Currently "4"; *Unknown Cause, Uncertainty in Corrective Action*."

5.0 Assessment Plan

This investigation establishes the IRT support for Phoenix Mission RA Brush Motor Failure within the NESC. It defines the mission, responsibilities, membership, and conduct of operations for this assessment.

This assessment was initiated out-of-board by the authority of the NESC Deputy Director on August 10, 2006. The objective was to identify the issues associated with the brush DC motors, provide recommendations for additional work, and to provide an assessment of the flight worthiness of the motors. The motors in question are on the RA of the vehicle and are mission critical.

An NESC IRT with relevant expertise was formed to perform the assessment. The IRT includes expertise in mechanical systems, electro-mechanical, and materials engineering proficiencies.

The IRT investigation was limited to teleconference and transfer of information electronically between the IRT and the Phoenix Project engineers. The information exchange process proved to be acceptable for the level of evaluation requested.

6.0 Problem Description, Proposed Solutions, and Risk Assessment

6.1 Problem Description

The anomalies with these motors occur in the commutating brushes. There are two failure modes that have been identified which are a concern for mission success (shown in Figure 6.1-1).

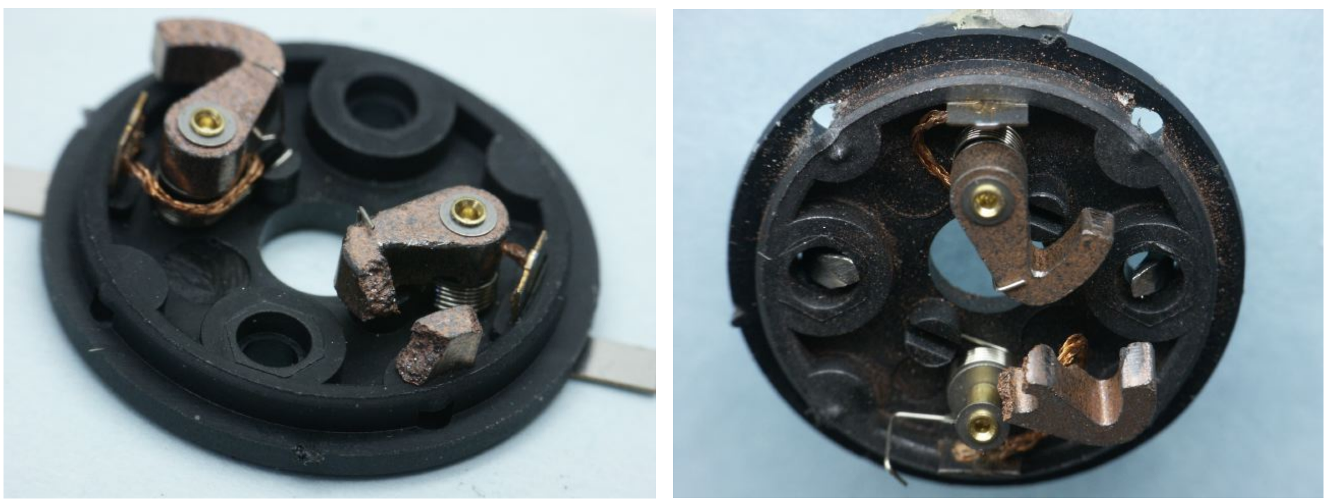


Figure 6.1-1. Motor Brush Anomalies – Tip Failure (Left) and Pivot Failure (Right)

For the MER Project, a total of 211 motors of this size were purchased. These motors are permanent magnet brush type DC motors manufactured by Maxon in Switzerland. The composite brushes were manufactured in Europe by suppliers to Maxon, in accordance with a JPL-developed formulation and provided to Maxon as GFE. Of the 211 brush DC motors, 168 were fully tested and flight-qualified for use on the MER Project. None of these motors showed any indication of degraded or broken brushes.

Several motors were used by the MER Project for simulated pyro shock exposure at the component level to assess their capability to meet anticipated in service shock loads. The motors failed to pass the specified pyro shock environment. Tests at different shock levels determined that the maximum level the motors could tolerate at the component level was 2,600 Gs peak SRS, well below the 4,000 Gs peak SRS requirement. It was only at the component level shock testing that resulted in broken brushes. No motor brush failures were detected during actual pyro shock testing at the assembly level. The shock environment for all motor locations were reassessed and some, but not all, of the applications were acceptable with no additional work.

“Red-Flag” Problem/Failure Reports (PFR) remained for three of the MER Project applications because, while no motors ever failed after exposure to the actual shock from pyrotechnics, the margin could not be demonstrated for the three remaining locations.

Simulated pyro shock testing at the component level routinely results in an overtest situation. The exact shock environment seen at the component level within the complete assembly is difficult to predict, while shock testing at the assembly level provides better fidelity and less (more realistic) risk to the hardware. This was demonstrated at the MER Project where 50 RE020 motors were integrated, tested, launched, placed on Mars, and operated successfully beyond their mission design life.

Prior to the MER launch, one motor was sent to the Kennedy Space Center (where the test equipment was located) for determining the condition of a test motor (component level) exposed to simulated pyro shock. The unit exhibited anomalous current traces, and failed to function upon return to JPL. The motor was found to have a broken brush at disassembly.

In addition to the 50 RE020 units now on Mars, 17 units were used in the MER Project test bed. The remaining units were placed in storage under the Flight Hardware Logistics Program (FHLP). For the Phoenix Project, 28 of these motors were retrieved from FHLP, including serial numbers (S/Ns) 40 and 60 which were found to be defective with broken commutator brushes Similar to other (26) motors pulled, these two motors were fully tested by the MER Project, but were not exposed to a shock environment before they were placed in FHLP. S/N 40 was one of the original four units that were part of the qualification program performed by the MER Project. S/N 60 was originally integrated into the MER Project flight spare high-gain-antenna gimbal (HGAG). S/N 60 was then de-integrated from the HGAG and assembled in the electron microscope autoradiography (EMRA) wrist. S/N 60 was replaced by S/N 101 after the motor failure was discovered during the Phoenix Project. No clear failure mechanism has been established for these two brush failures. It was suggested, but cannot be substantiated, that adverse handling may have precipitated the breakage. There appear to have been no special handling and storage procedures in place beyond the care normally exercised with flight hardware. Figure 6.1-2 illustrates the flow and processing of S/N 040 and 060.

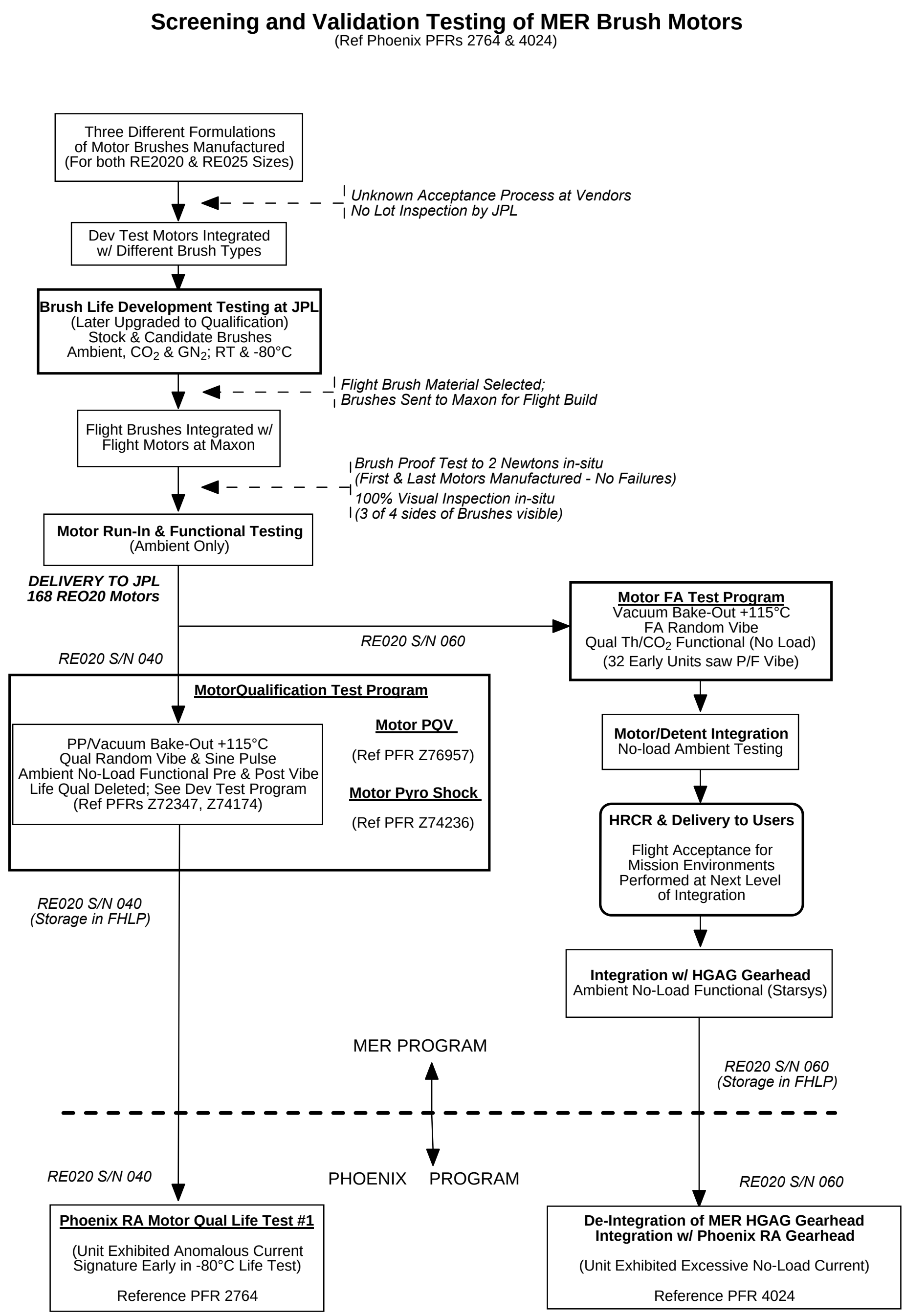


Figure 6.1-2. History of Failed Brush Motors S/N 040 and 060

6.2 Proposed Solutions

A series of screening tests (electrical and auditory) were conducted to evaluate the flight motors prior to RA integration. The acceptance of the motors for the Phoenix Project RA relied primarily on the detailed "motor health checks" previously performed during the MER Project. These involved the standard static measurements such as motor resistance, insulation resistance, and dielectric breakdown as well as detailed examination of the high bandwidth current traces during initial operation. If any of the static measurements of a motor performance were outside the normal range, it would have been flagged to receive further scrutiny and, depending on the aggregate results, could be rejected for flight.

The motor current traces were examined for current noise and symmetry between clockwise and counter-clockwise rotation. As shown from measurements on motor S/N 40 containing a brush with a broken tip, the initial current is noisy and asymmetrical due to poor conformance of the brush contact surface to the commutator. However, after running the motor for a brief period of time, the brush can wear and regain conformity to the commutator contour. Current noise and symmetry measurements, likewise, return to nominal levels. This indicates there can be a lack of assurance with only post exposure electrical testing. The motor operation appears to be healthy based on current noise and symmetry characteristics, but its life may be limited because of the reduction in the amount of available brush material.

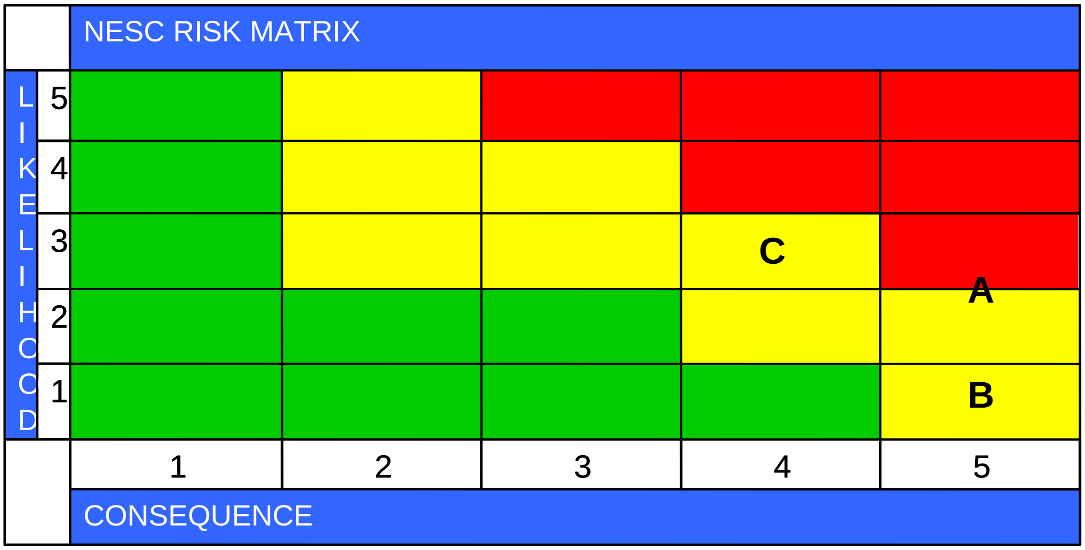
Although the low resolution electrical tests performed provide some confidence for acceptance of the motors for flight, these tests are not definitive for long term operational performance. In an attempt to enhance the evaluation of the motors for flight acceptance, and to screen degraded brushes performing acceptably for the short term, an auditory test was developed. Broken brushes can leave debris in the motor housing. By manipulating the motors in different orientations while energized, the brush debris may move by the force of gravity and can contact the rotating armature, resulting in a noise that can be audibly detected. If these sounds are perceptible, the motor could be further evaluated and potentially rejected from flight. The success of the auditory test is highly dependent on the presence and size of the particles generated, and also assumes the motor has not seen additional operation pulverizing debris prior to conducting the auditory test.

At this time, efforts have been concentrated on verifying that the brush motors within the assembled RA are acceptable for flight using the latest techniques available developed to detect broken brushes. On June 9, 2006, prior to starting RA environmental testing, two motors were checked in situ using the auditory test technique. All four motors in the RA were verified using the auditory technique on June 27 and 28, 2006, after the RA was tested to proto-flight levels. The RA was articulated to position each joint motor in proper orientation relative to gravity to perform the auditory test. No anomalous auditory signatures were detected. The electrical "motor health checks" were not performed because of difficulties integrating the high resolution electrical equipment into the Phoenix Project EGSE. Low resolution electrical measurements were performed. The successful completion of these tests (auditory and low resolution electrical) on all four motors integrated into the RA is relied on to accept the motors for flight.

Additional effort to X-ray the motors to obtain an indication of the brush condition was made, but proved unsuccessful due to the housing assembly shielding the brushes from adequate observation. Fine-focus X-ray on the motors and brushes intended for flight was performed, but the density of the brushes is too low to be discerned after penetrating the housing. Furthermore, when looking at the brushed in "plane view" (from the end), the motor metallic elements prevented any viewing of the brush. Since all avenues to use X-ray failed on the MER Project, X-rays for the Phoenix Project motors prior to integrating the motors into the RA were not performed.

6.3 Risk Assessment

The following risk assessment was generated by the IRT. The Phoenix Project risk assessment was conducted using a different methodology FC/CA that does not map directly to the 5x5 risk chart shown in Figure 6.3-1. No 5x5 risk assessment on this subject was conducted by the Phoenix Project at the time of this report date. However, an attempt was made by the IRT to correlate the identified risks for Hazard Event A to the risk matrix. The following chart provides an explanation of the combined IRT and Phoenix Project risk assessments. It was the consensus of the team that the best way to illustrate the Phoenix Project risk was to break it into two parts or two separate failure modes. The first is a brush root break where a failure would be noticed shortly after occurrence in functional testing. The second is a tip break which would be much more difficult to identify, but would also have a lower consequence for the mission.



HAZARDOUS EVENTS

A – Initial Assessment

B - Brush Root Break (Post Assessment)

C - Brush Tip Break (Post Assessment)

* The initial risk assessment performed by the Phoenix project was conducted using the JPL FC/CA methodology and does not correlate exactly to this 5x5 matrix.

Figure 6.3-1. 5 x 5 NESC Risk Assessment

The conclusion that a complete brush failure has a consequence rating of 5 most likely can be applied to 1 of the 4 RA motors and therefore drives the overall risk rating. As indicated by the Project Systems Engineer, for most, but not all mission objectives, a single motor loss of any but one particular joint in the RA would not result in a complete mission failure (meeting minimum mission criteria).

The initial assessment Likelihood of 2.5 is based on the NESC definition, "Likely to occur some time in the life of the item. Likelihood of occurrence is estimated to be between 0.001 and 0.01 (10-3 and 10-2) per operational opportunity" in addition to an interpretation of the JPL FC/CA descriptions. Table 6.3-1 illustrates the various parameters which contributed to this assessment and the underlying rationale.

Table 6.3-1. Risk Likelihood Assessment Rationale

Uncertainty Category	Likelihood	Known Facts / High Success Confidence	Unknowns / Uncertainties
Brush Strength	3		> Strength Test Data from 2006 indicates large scatter. Probability analysis eliminated a low strength outlier from which there is no proof that flight parts are not also outliers. > Also, 2 brushes were damaged when removing from the SEM. Were these also Low Strength brushes? > Comparison to flight loads does not include dynamic amplification.
Brush / Motor Storage	3	> Standard flight hardware handing and storage.	> Brushes were originally manufactured for MER in 2000. > Brush components, prior to integration into motors, were not stored individually or protected with great caution between brush manufacture and delivery to motor manufacturer. (They were stored in one big bag.)
Brush / Motor / System Handling	3	> Standard flight hardware handing and storage.	> No special handling based on the fragility of the brushes.
Brush Inspection Opportunities	3		> Once assembled into a motor, only N-Ray can be used to detect a broken (separated) brush. > Not possible to detect a cracked brush. > No inspection possible once installed into the system assembly.
Motor Level Testing	2	> First lot of 32 units exposed to Protoflight dynamics; all others experienced FA dynamics. All units (211 total) exposed to vacuum bake-out and qual cold no-load functional test. All but two subsystem motor applications (eventually) passed simulated pyro shock qualification. The design passed thermal cycling PQV testing.	> 3 (out of 211) motors from original delivery did not pass acceptance testing due to excessive electrical noise and/or failure to meet cold no-load speed criteria. > A number of motors failed under simulated pyro shock testing. Additional motors were retested and passed with a lower, more realistic pyro shock level and passed temperature cycling PQV testing. > 2 motors transferred from MER/FHLP (S/N 040 & 060) successfully completed Acceptance Testing (MER) and were placed in controlled stores. These motors were later removed for use on Phoenix and found to have broken brushes.
Subsystem Level Testing	1	> All Subsystems containing brush motors survived Protoflight-level testing without motor anomalies. Subsystem level tests included temp/atmosphere (N_2 and/or CO_2) and protoflight dynamics (qual levels for 1 minute duration). Simulated pyro shock was not experienced at the Subsystem level, but some subystem motors sustained actual pryo shock without anomaly. Approximately 50 MER flight motors, 17 MER Qual motors, and a number of (uncounted here) motors used in development were subjected to dynamics and temp/atmos testing without anomaly. Additionally, 8 Phoenix flight motors sustained Subsystem Protoflight dynamics, temp/atmosphere, and two series of pyroshock tests without anomaly.	
System Level Testing	1	> All motors for MER and Phoenix survived System level testing to date with no anomalies attributed to motor brush failures.	
Number of Failed Brushes Out of Lot	2		> 2 brushes (1 of 2 on each motor S/N 040 & 060) out of 211 motors fell through the initial screening procedures and ended up in the flight available stock until found during subsequent Phoenix testing.
MER Flight History	1	> 50 motors used for MER Flight program (25 per Rover) without any known anomalies attributed to brush failures. Motors used in both deployable (14) and continuous (11) use applications. Motors successfully functioned on Mars sustained Subsystem testing, System Testing (in some cases twice), and launch/landing environments.	
Final Motor Verification Opportunities	2	> "Aliveness Test" only possible after shipping to KSC. Briefly powered in the stowed position to verify continuity, and slight encoder motion.	> Post Systems Test Functional Verification of motors (includes "listening" test) prior to shipping to KSC.

The risk events were broken into two parts, a root break and a tip break. As discussed in more detail within this report, a brush failure at the pivot (root break) is catastrophic to the motor, but there is a high likelihood that it will be detected through motor functional and system level testing.

A tip break is less likely to be detected during functional testing; however, a tip failure can still allow motor function but with a possible reduction in torque margin and/or life. There is some concern that a tip failure is an indication of brush strength on the low end of the data scatter; however, the strength of the weakest brush tested is still greater than 3x the predicted worst case qualification loads. Because of the motor functionality with a tip failure, the consequence is listed as a 4.

The implementation of additional risk mitigation actions (additional testing and/or inspection), or following the recommendations stated within this report, could reduce the likelihood estimation, but would not produce any change to the consequence. Only a change to the brush design or alternate motor would change the consequence estimation.

The Phoenix Project Failure Assessment Matrix is provided in Appendix C. The initial risk assessment conducted by the Phoenix Project utilized the following:

Failure Effect Rating “3”; *Major Degradation or Total Loss of Function*
Failure Cause/Corrective Action Rating Currently “4”; *Unknown Cause, Uncertainty in Corrective Action*

JPL Problem/Failure Report (PFR) Risk Ratings:

Two number system, the first number being "Failure Effect (FE) Rating" and the second being "Failure Cause/Corrective Action (FC/CA) Rating".

<u>Failure Effect Rating 1</u>: *Negligible*
- Negligible degradation of required functional capability of Payload or spacecraft.
- Negligible degradation of engineering or science telemetry.
- Negligible increase in operational difficulties or constraints.
- Negligible reduction in lifetime.
- Support, test, or facility equipment problem/failure.
- Support, test, of facility operator induced problem/failure.
- Workmanship failure found at first scheduled test opportunity.
- Problem/failure could not occur in flight.

<u>Failure Effect Rating 2</u>: ***Significant***

- Significant degradation or functional capability of Payload or spacecraft.
- Significant degradation of engineering or science telemetry.
- Significant increase in operational difficulties or constraints.
- Appreciable reduction in lifetime.

<u>Failure Effect Rating 3</u>: ***Major degradation or total loss or functional capability of Payload or spacecraft.***

The Cause/Corrective Action Rating is an assessment of the certainty that the exact failure cause has been determined and the corrective action will eliminate any known possibility of recurrence of the problem/failure in flight. The numeric rating shall be 1, 2, 3, or 4 based on the following criteria:

<u>Rating 1</u>: ***Known Cause/Certainty in corrective action. No known possibility of recurrence.*** Analysis, corrective action, and verification of correction are considered to have determined the cause and have defined an effective corrective action that has been implemented and verified by test or other demonstration. The effectiveness of the corrective action is certain; therefore, there is no residual flight risk.

<u>Rating 2</u>: ***Unknown Cause/Certainty in corrective action. No known possibility of recurrence.*** The cause could not be completely determined, but an effective corrective action has been implemented and verified by test or other demonstration, or the problem/failure (observed incident) could not be repeated in tests or checkouts. The effectiveness of the corrective action is certain and, therefore, there is no residual flight risk.

<u>Rating 3</u>: ***Known Cause/Uncertainty in corrective action. Some possibility of recurrence.*** Analysis, corrective action, and verification of correction are considered to have determined the cause, but effective corrective action has not been implemented and verified by test or other demonstration. The absolute effectiveness of the corrective action is uncertain; therefore, there is some residual flight risk.

<u>Rating 4</u>: ***Unknown Cause/Uncertainty in corrective action. Some possibility of recurrence.*** The cause could not be completely determined and no effective corrective action has been implemented and verified by test or other demonstration. The absolute effectiveness of the corrective action is uncertain; therefore, there is some residual flight risk.

7.0 Data Analysis

An investigation of the analyses and screening tests conducted by the Phoenix Project during the design and build phase of these DC motors was conducted by the NESC IRT. It was concluded that screening tests (electrical and auditory) conducted were the best possible with the available equipment. However, additional non-invasive, nondestructive evaluations could be done to increase the confidence of the brush integrity. It was suggested by the IRT that one potential nondestructive evaluation technique, N-ray examination may resolve the condition of the brushes inside the motor. Therefore, an N-ray evaluation was performed on two non-flight motors to evaluate the potential of this technique.

In addition, examination of the environmental stability and material lot acceptance of brush material was also examined.

7.1 N-Ray Test Summary

An investigation was conducted by the IRT to show how effective N-ray would be for examination of the brush motor design. Two motors were evaluated, as shown in Figures 7.0-1 and 7.0-2.

Figure 7.0-1 (Image 6304) depicts the interior of a partial motor assembly (missing the encoder assembly). The brushes were intentionally installed incorrectly by not spring-preloading against the commutator. If N-ray could not detect this workmanship flaw, then it was doubtful N-ray would be beneficial as a rigorous nondestructive tool.

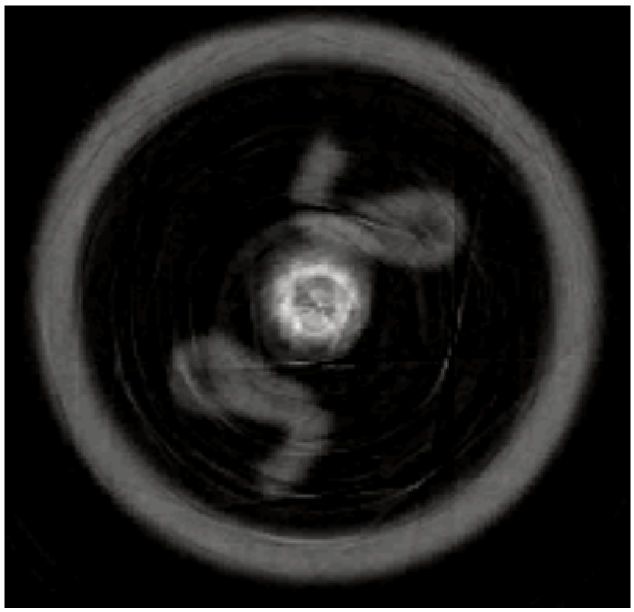


Figure 7.0-1. Image 6304 Motor N-Ray Image (Brushes Intentionally Not in Position)

Figure 7.0-2 (Image 6305) depicts a scan of a fully assembled motor with the encoder assembly included.

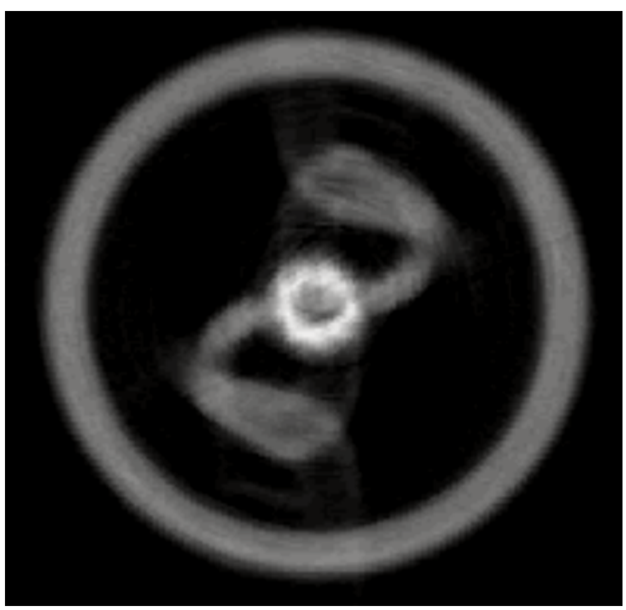


Figure 7.0-2. Image 6305 Motor N-Ray Image

These inspections were performed by the McClellan Nuclear Radiation Center at University of California (UC)-Davis. "Conventional" N-ray imaging, where the motor is placed on film (as the detector) and irradiated by an N-ray source, was of limited value. The brushes were detectable in the side view, but not from the end view where their full shape and the loss of any macroscopic pieces could be observed. The imaging is state-of-the-art in that they are produced by an N-ray equivalent to Computed Tomography (CT) scanning. It took nearly a full day to produce each of the two images.

As Figures 7.0-1 and 7.0-2 shows, the graphite brushes are distinctive in both scans. When the images were magnified and slowly stepped through the sequential scans, some variation in the "density" of the brush was observed. This density variation however, is an artifact of the scan-and-reconstruction process. The use of N-ray beyond the detection of macroscopic breaks in the brushes would require an involved development effort to determine if flaws or pre-existing cracks could be detected.

Therefore, the following can be concluded from this test:

1. N-ray imaging can distinguish the copper/graphite brushes within an assembled motor.
2. Gross workmanship errors and, potentially, macroscopic brush breakage can be detected by N-ray scan imaging without destructive disassembly of the motor.
3. N-ray scans should be able to detect a brush "tip break", or the brush "pivot break not displaced from the pivot".
4. N-ray should be able to penetrate any metallic overshield or housings around an integrated motor. However, it is currently not known whether Kapton™[1] tape overwrap or Kapton™ film heaters around a motor, integrated at the next level of assembly, would interfere with the imaging.

7.2 Environmental Stability of Molybdenum Disulfide (MoS_2)

The copper/graphite motor brushes used for Phoenix Project contain MoS_2 and were stored in the FHLP in an uncontrolled environment. The chemical conversion of MoS_2 is documented in open literature and facilitated by time and exposure to heat and humidity. This chemical conversion of MoS_2 would result in a higher coefficient of friction.

[1]A registered owner of DuPont De Nemours and Company Corporation, Delaware

In general, MoS_2 is sensitive to humidity at, or above, 40 percent RH. The sensitivity increases when high humidity is combined with heating. In humid environments, MoS_2 can be converted to molybdenum oxide and hydrogen sulfide. Molybdenum oxide has a high coefficient of friction than MoS_2. Hydrogen sulfide is acidic and potentially can have negative consequences to metal surfaces. Again, this behavior is more of an issue under humidified conditions exceeding 40 percent RH and at higher temperatures. This conversion is slow, but with significant exposure times, the entire MoS_2 layer can be converted.

On the positive side, the molybdenum oxide layer can usually be removed during normal operation via wearing through the higher friction layer and eventually arriving at the MoS_2 layer.

There was inspection of the brushes for composition, but only at the fractured surface and not at the original exposed surface of the brushes where conversion of the moly would have been evident. Also, EDS may or may not have detected the oxide layer depending upon its thickness due to the sub-surface penetration of the EDS.

7.3 Brush Material Lot Acceptance

The motors and all brushes were manufactured for the MER Project in early 2001. All brush components tested for strength were from the same lot of brushes that went into the motors. The strength test report is included in Appendix D. Table 7.3-1 provides a breakdown distribution of the motors built for MER and Phoenix.

Table 7.3-1. RE020 Motor Usage and Residual Stock

RE020 Motor Usage	Quantity	Balance	Comments
Total Motors delivered to JPL	---	211	
Number of motors rejected for various reasons (Motor Yield for Flight Use)	43	168	43 motors deemed non-flt due to mfg or test anomaly (NOT broken brushes)
MER Flight Hardware	50	118	25 motors for each system
Earth Test Bed Rover	17	101	
Phoenix Flight RA	4	97	
Phoenix EM RA	4	93	
Recent Motor Screening for Brush Breakage from FHLP Flight Stock	8	85	Destructively Evaluated
Motors used for various qualification tests, engineering evaluations, pyro shock testing, and destructive evaluations.	71	14	Residual balance is spare flight quality motors in FHLP.

The first two series of brush strength tests were performed for the MER Project in December 2003. The next three series of brush tests were performed for the Phoenix Project in 2006 (see Appendix D). There were no obvious differences in the strength of the brushes between the first series of tests for the MER Project (which investigated temperature effects) and the Phoenix Project series (which added vacuum bake-out and thermal cycling).

7.4 Brush Design

It appears that a brush break resulting from increased friction at the interface was deemed not possible because it is stated that this would only occur with metal brushes. This failure mode was observed in a different design brush motor used in an earlier project. The brush design was a cantilevered metal leaf with a platinum-silver brush. Unlubricated, insufficient life was exhibited. When lubricated with Braycote®[2] grease, life was acceptable but, under cold

[2] A registered owner of the Castrol Industrial North America Inc. Corporation Delaware

operation, one brush would fail in bucking because the adhesion of the brush to the commutator was greater than the buckling strength of the cantilevered beam.

All of the Phoenix Project motors are designed for bi-directional operation. Both brush bodies are in shear/tension in one direction of rotation and in shear/compression in the other direction of rotation (assuming non-zero sliding friction). The hooked "arm" of both brushes depicted in Figure 7.4-1 is bending at the "elbow" in either direction of rotation.

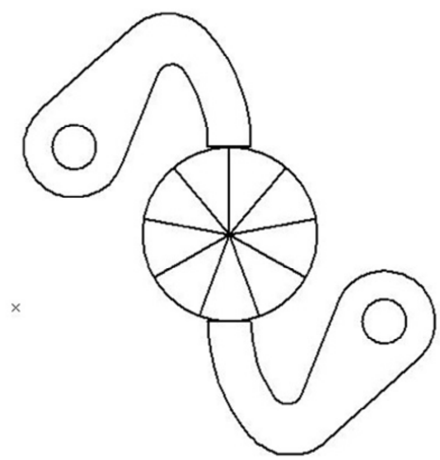


Figure 7.4-1. Brush Motor Armature/Commutator Design

8.0 Findings, Observations, and Recommendations

8.1 Findings

F-1. Specific handling procedures were not available to ensure minimum risk to impact damage to flight hardware.

F-2. Fine-focus X-ray inspection is ineffective in resolving brush degradation.

F-3. N-ray inspection can resolve macroscopic brush damage, but requires development to determine if cracking or other microscopic flaws can be reliably detected.

F-4. The storage of the motors in an uncontrolled environment has potential to chemically convert the MoS2 in the copper/graphite brushes causing an increase in the coefficient of friction.

F-5. One material lot with acceptable strength and thermal stability characteristics was used for the brush components used for all motors in the MER and Phoenix Projects.

F-6. The bi-directional motor operation places complex reverse loading on the brush design which requires proper friction interaction with the commutator to minimize failure.

F-7. The final RA motor functional and “listening” test will occur post system environmental testing, but prior to shipment to KSC. Post shipment testing at KSC will include an "Aliveness Test" only where the motors will be briefly powered in the stowed position to verify continuity, and slight encoder motion.

8.2 Observations

O-1. The Phoenix Project performed a detailed investigation into the motor brush anomalies. However, there was no apparent attempt to investigate an alternate plan that would implement a different motor or brush design. Although a system redesign and recertification would have been laborious, it may have provided an overall lower (likelihood and consequence) risk to the Phoenix Project.

8.3 Recommendations

R-1. To reduce the risk for a LOM due to undetected motor brush degradation, the Phoenix Project should conduct a nondestructive inspection such as N-ray for evaluation of the RA DC motors as late in the assembly level as practical. However, once the RA has reached system level testing on the vehicle, removal of the motors for inspection is not recommended due to the potential for damage from the additional transportation and handling. (***F-1 and F-3***)

- If inspection occurs on motors separated from the RA, then specific handling instructions should be generated to minimize risk to any additional damage.

R-2. For transportation to KSC, apply monitoring accelerometers as near as possible to the RA. Evaluate shock acceleration levels exceeding 75 g's to determine the loading at the RA motors. (***F-7***)

- Per JPL IOM 3550-DN-0647, "Load Equivalents on RE020 Motor Brushes," peak accelerations in excess of 75 g's axial are necessary before relative brush movement within the motor occurs. This is felt to be a safe limit for protecting the brushes.

9.0 Alternate Viewpoints

No alternative or dissenting opinions were identified in the submission of this report.

10.0 Other Deliverables

No deliverables were identified in the submission of this report.

11.0 Lessons Learned

LL-1. Brush motors are problematic and should be avoided where possible for space missions. As stated in the NASA Space Mechanisms Handbook (NASA/TP-1999-206988): "The most common material for brushes is graphite, but graphite brushes are generally unsatisfactory for under vacuum conditions. The water vapor present in air bonds to the π electrons in the graphite, decreasing bonding between the hexagonal layers, allowing them to slide easily over each other, and thus providing lubricating properties normally associated with graphite. In a vacuum there is no water vapor to tie up these bonds, the layers do not slide, and the graphite tends to powderize."

Also, American Institute of Aeronautics and Astronautics (AIAA)-S-114 (Moving Mechanical Assemblies for Space and Launch Vehicles) states: "Direct current brush motors may require special design and brush selection to avoid arcing or debris generation in both partial and high vacuum, as well as during ground testing."

It is understood that operation in the Martian environment does not constitute a hard vacuum and the lubrication issues will be less severe; however, the lubrication and material strength issues associated with this design for earth ground operation and mission performance results in higher program risk than other alternative designs.

LL-2. N-ray imaging is a good inspection technique when X-ray does not provide the appropriate penetrating image. Neutrons are attenuated by matter either by scattering from the nucleus of a target atom or through absorption by that nucleus. Elements that are close together in atomic number will have similar X-ray attenuation and yet may have markedly different neutron attenuation characteristics that can be detected through neutron radiography. This makes possible a suite of inspections that can not be done with other radiographic techniques such as imaging light elements inside heavier elements, i.e., wax inside lead or hydrogenous materials inside metal.

12.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left

	uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Problem	The subject of the technical assessment/inspection.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	An action identified by the assessment team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Requirement	An action developed by the assessment/inspection team to correct the cause or a deficiency identified during the investigation. The requirements will be used in the preparation of the corrective action plan.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

13.0 Acronyms List

AC	Air Conditioner
AIAA	American Institute of Aeronautics and Astronautics
CT	Computed Tomography
DC	Direct Current
DPA	Deflection Plate Analyzer
EGSE	Electrical Ground Support Equipment
EM	Engineering Model
EMRA	Electron Microscope Autoradiography
FC/CA	Failure Cause/Corrective Action
FE	Failure Effect
FHLP	Flight Hardware Logistics Program
FM	Flight Model
GFE	Government-Furnished Equipment
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center

HGAG	High-Gain-Antenna Gimbal
IRT	Independent Review Team
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LaRC	Langley Research Center
LOM	Loss of Mission
MER	Mars Exploration Rover
mm	Millimeter
MoS_2	Molybdenum Disulfide
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Evaluation
NESC	NASA Engineering and Safety Center
N-Ray	Neutron radiography
NRB	NESC Review Board
PFR	Problem/Failure Report
RA	Robotic Arm
S/N	Serial/Number
SRS	Shock Response Spectra
TDT	Technical Discipline Team

Volume II: Appendices

Appendix A. ITA/I Request Form (NESC-PR-003-FM-01)

NASA Engineering and Safety Center
Request Form

Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov, or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681

Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 8/10/2006 12:00 AM	Status: New	Reference #: 06-050-E
Initiator Name: Brian Muirhead	E-mail: brian.k.muirhead@jpl.nasa.gov	Center: JPL
Phone: (281)-483-0716, Ext _____	Mail Stop:	
Short Title: Independent Review Support for Phoenix Mission Robotic Arm Brush Motor Failure		
Description: The Phoenix mission (Phoenix is Mars Scout mission to land at the Northern latitudes of Mars and probe the surface for ice, launch is July, 2007) has a major mission risk issue due to their finding 2 broken brushes in the set of motors to be used for the robotic arm. The operation of this arm is mission critical and the motors are single string. These motors are from the MER build and the cause of the breakage is unknown. JPL's mechanical engineering division has evaluated the problem and prepared a thorough assessment and recommendations that the project is following. To provide further assurance that every avenue has been investigated, the Mars Program office has requested the JPL OCE conduct an independent review. The OCE has agreed to conduct the review and requested support from the NESC.		
Source (e.g. email, phone call, posted on web): e-mail		
Type of Request: Consultation		
Proposed Need Date:		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 8/10/2006 12:00 AM		
Potential ITA/I candidate? ☒Yes ☐ No		
Assigned Initial Evaluator (IE): This was approved Out-of-Board by Ralph Roe on 8/10/2006. It will be lead by John McManamen		
Date assigned (mm/dd/yyyy):		
Due date for ITA/I Screening (mm/dd/yyyy):		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? ☒Yes ☐ No		
If yes:		
Description of action:		
Actionee: o		
Is follow-up required? ☐Yes ☐ No If yes: Due Date:		
Follow-up status/date:		
If no:		
NESC Director Concurrence (signature):		

NESC Request Form
NESC-PR-003-FM-01, v1.0
Page 1 of 3

Request closure date:		
Section 3: Initial Evaluation		
Received by IE: (mm/dd/yyyy h:mm am/pm):		
Screening complete date:		
Valid ITA/I candidate? ☐Yes ☐ No		
Initial Evaluation Report #: NESC-PN-		
Target NRB Review Date:		
Section 4: NRB Review and Disposition of NCE Response Report		
ITA/I Approved: ☐Yes ☐ No	Date Approved:	Priority: - Select -
ITA/I Lead: , Phone ( ) - , x		
Section 5: ITA/I Lead Planning, Conduct, and Reporting		
Plan Development Start Date:		
ITA/I Plan # NESC-PL-		
Plan Approval Date:		
ITA/I Start Date	Planned:	Actual:
ITA/I Completed Date:		
ITA/I Final Report #: NESC-PN-		
ITA/I Briefing Package #: NESC-PN-		
Follow-up Required? ☐Yes ☐ No		
Section 6: Follow-up		
Date Findings Briefed to Customer:		
Follow-up Accepted: ☐Yes ☐ No		
Follow-up Completed Date:		
Follow-up Report #: NESC-RP-		
Section 7: Disposition and Notification		
Notification type: - Select -	Details:	
Date of Notification:		
Final Disposition: - Select -		
Rationale for Disposition:		
Close Out Review Date:		

NESC Request Form
NESC-PR-003-FM-01, v1.0

Page 2 of 3

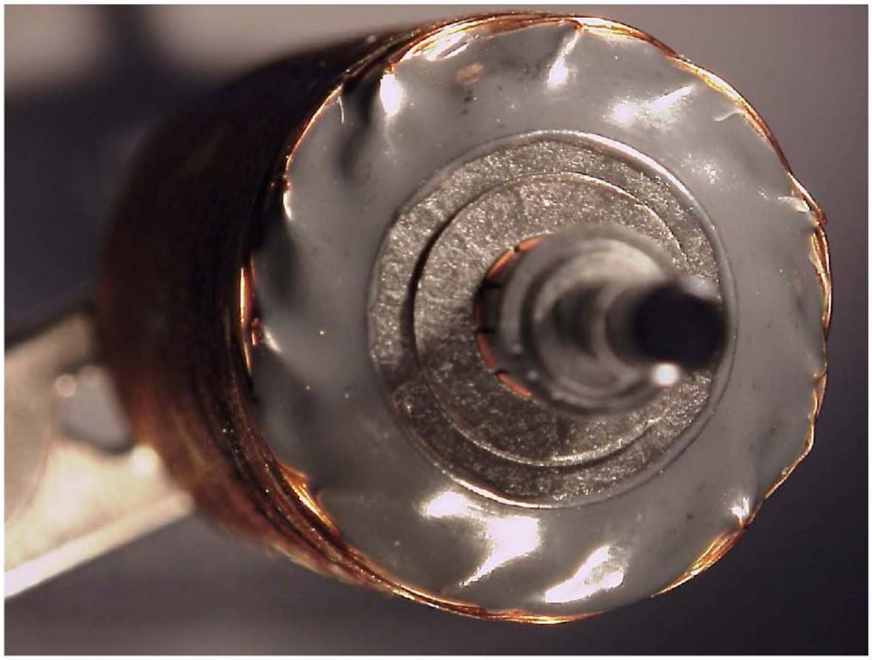
Form Approval and Document Revision History

Approved: ______________________________ ____________
NESC Director Date

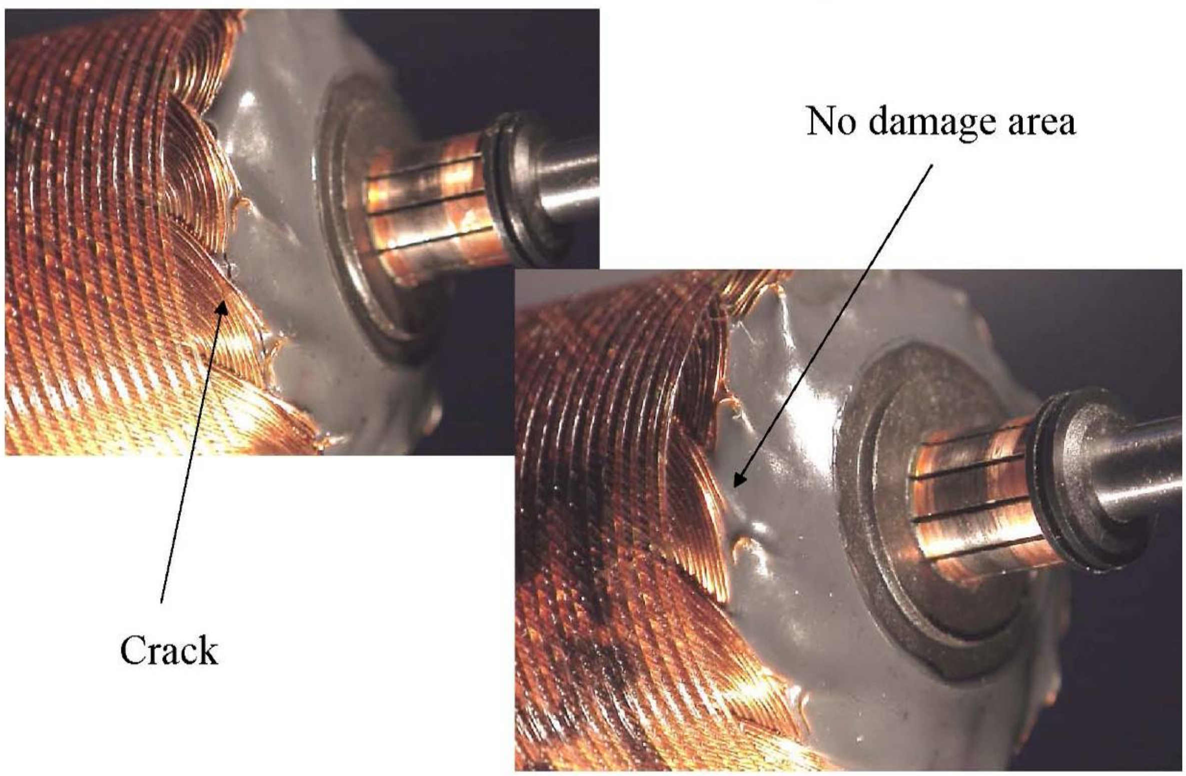
Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

Appendix B. Rotor Photographs

Maxon Motor, Failure #55-Pyroshock



Maxon Motor, Failure #55-Pyroshock



Appendix C. Phoenix Project Failure Assessment Matrix

	Fault Description	Objective Evidence or Argument	Possibility as Root Cause
1	Brush Broken at Delivery to JPL from Maxon (Pre-existing Flaw)	S/N 040 & 060 passed MER Qual and FA testing (respectively, see Screening & Validation Testing Flow Chart). Possibility, with very low likelihood, that pre-existing damage could have been undetected through MER Acceptance Testing. "First and last" motors subjected to a pre-cap proof test of brush *in situ* at Maxon.	Arguably possible, cannot be ruled out
2	Handling Damage; Post-MER Storage to Phoenix Usage	No objective evidence of handling damage (such as dented or marred housings), and no report of mishandling during storage. Motors S/N 040 & 060 "took different paths" to Phoenix program. "Drop tests" demonstrated that motor brushes can be broken from 2 foot drop to floor, although very unlikely to result in S/N 040 failure.	Quite possible, but likelihood questionable
3	Brush Damaged by Previous Environmental Testing	Brushes demonstrated to be broken by simulated pyro shock testing (Reference PER Z74236), which these motors did not experience. No MER motor brushes damaged from multiple vibration test cycles (Qual & FA), including sine burst & pyro firings, although low possibility exists that some forms of brush failure could be passed undetected. However, 168 motors passed testing for MER; 73 units utilized for Mars mission or ground test-bed have exhibited no anomalies, PLUS all 65 residual flight motors re-screened with new techniques for Phoenix, and no brush breakage was detected.	Unlikely
4	Accumulated Damage to Brush (Material Fatigue)	SEM Analysis: No evidence of secondary cracking; Strain involved is too low for low cycle fatigue.	Unlikely
5	Low Temperature Creep	SEM Analysis: Imparted loads are below creep limit. S/N 040 broke in area of compression, not tension or bending.	Unlikely
6	Damaged from Thermal Cycles	No brush damage was detected as a result of MER PQV Qualification (7 units; Reference PFR Z76957)	Unlikely
7	Brush Sticking (Adhesion) to Motor Rotor	No evidence of this being possible (occurs with unlubricated metal brushes).	Not Possible

	Fault Description	Objective Evidence or Argument	Possibility as Root Cause
		Failure of S/N 060 in low stress zone of brush.	
8	Damaged by Thermal Shock	Failed motors not subjected to rapid temperature swings. MER PQV Qual subjected motors to most rapid temp swings with no effect to brushes.	Not Possible
9	Damaged by Temperature Extremes	Temperature exposure of these units not unique; within MER range.	Not Possible
10	Damaged by High Current through Brush	No known mechanical stress or chemical change from current (other than related to temperature rise in brush). Other motors experienced higher current without damage; Motor S/N 060 broken in area where no current flows.	Not Possible
11	Aging Degradation	No evidence of degradation. All motors working on MER (one potential exception). Recent brush strength testing "in-family" with pre-launch testing.	Not Possible

Appendix D. Motor Brush Strength Test Results

JET PROPULSION LABORATORY **INTEROFFICE MEMORANDUM**

3536-MK-06021
8/24/2006

To: D. Sevilla

From: Mike Knopp

Subject: RE020 Brush Strength Analysis

Reference: IOM 352H-DL-02-114, Summary of Testing of MER Motor Brushes

Summary

Samples of RE20 Motor Brushes were inspected using a SEM and mechanically tested after thermal conditioning. The data obtained from the mechanical testing was statistically analyzed to determine a probability of failure for a given load. The predicted flight loads for the brushes are under the minimum predicted breaking strength.

Sample Testing

Samples of RE020 Motor Brushes from the same lots used for the flight build were mechanically tested in bending to determine their breaking strength. Prior to testing, the brushes were subjected to a simulated Planetary Protection Bakeout and thermal cycling to represent environmental conditions flight motors were exposed to. The thermal conditioning was performed on two separate batches of brushes, randomly selected from the flight lot. The first batch contained 12 brushes and the second contained 8 brushes.

The parameters for the bakeout and thermal cycling are given in Table I.

Table I: Thermal Conditioning Parameters

	Temperature, °C	Duration	Pressure (torr)	Notes
Simulated Planetary Protection Bakeout	115	50 hours	$<10^{-3}$	Brushes were placed in a bag, purged with dry nitrogen, and sealed after the P.P. bakeout and again after thermal cycling
Thermal Cycling	-80 to 110 Ramp rate not to exceed ± 5 °C/ minute	10 cycles	$<10^{-3}$	

The first batch of twelve brushes were visually inspected at 10x prior to thermal conditioning and again inspected at high magnification using a SEM after mechanical testing. The second batch was inspected using a SEM prior to thermal conditioning, after thermal conditioning, and after mechanical testing. Two of the brushes in the second batch were damaged while attempting to remove them from the SEM stage prior to mechanical testing. Due to this damage, only six brushes from batch two were mechanically tested. No anomalies were identified during the inspection. A detailed report on the inspections is provided in memo 3536-SD-06022, Microscopic Examination of Phoenix Actuator Motor Brushes, prepared by Saverio D'Agostino.

The results from the testing of the RE020 Motor Brushes are given in Table II.

Table II: Mechanical Testing Results

Batch 1 Phoenix Testing
4/15/2006

Brush Condition: Simulated PP bakeout (50 hrs @ 115°C, 10^-3 torr)
10 thermal cycles, -80 to 110°C, <10^-3 torr

Sample Number	Breaking Load, lbs
1	0.196
2	2.3585
3	2.715
4	2.251
5	1.7185
6	1.7455
7	1.836
8	2.1555
9	1.9655
10	2.1725
11	1.8845
12	1.7895

Max	2.715
Min	0.196
Average	1.90
Std Dev	0.612

Batch Two Phoenix Testing
6/23/2006

Brush Condition: Simulated PP bakeout (50 hrs @ 115°C, 10^-3 torr)
10 thermal cycles, -80 to 110°C, <10^-3 torr

Sample Number	Breaking Load, lbs	
1	3.0495	
2	3.9015	
3	NA	Brush was damaged during removal from SEM stage
4	4.2605	
5	2.6855	
6	2.51	
7	NA	Brush was damaged during removal from SEM stage
8	2.9565	

Max	4.2605
Min	2.51
Average	3.23
Std Dev	0.698

Statistical Analysis

After the completion of mechanical testing, a statistical analysis was performed on the data. Figure 1 show the results of a three parameter Weibull data fit.

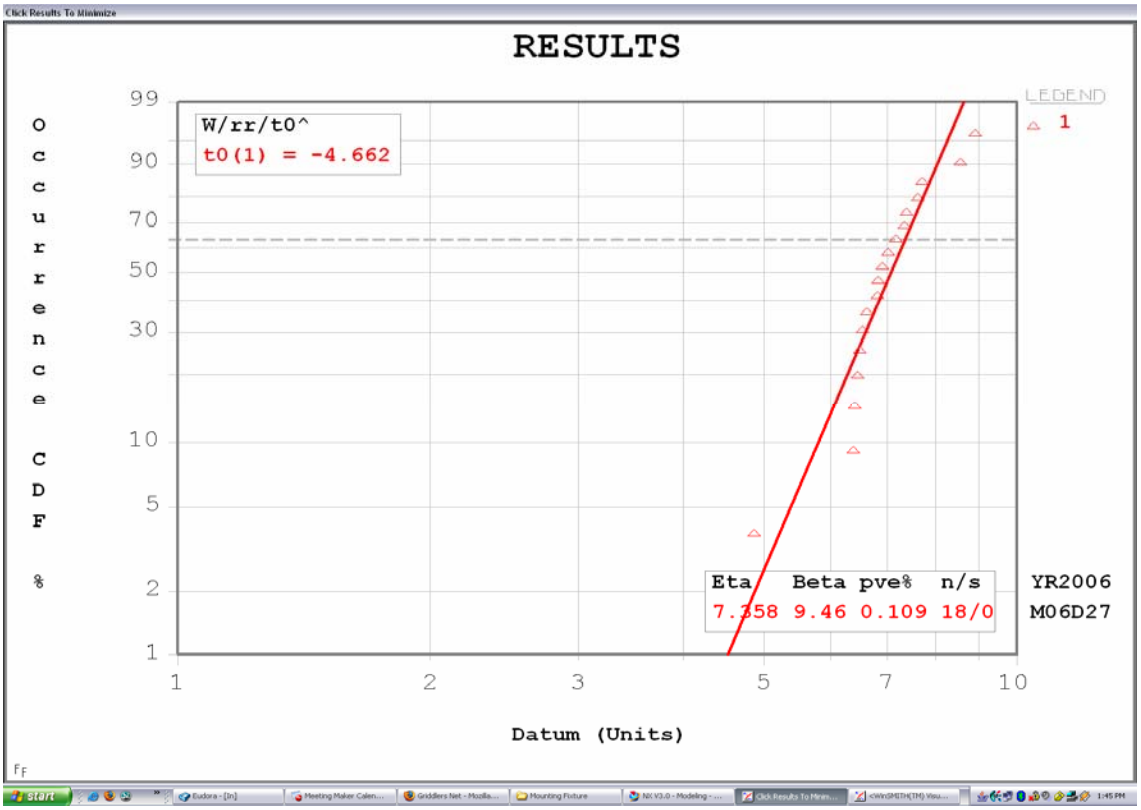


Figure 1. Three Parameter Weibull with Outlier

As shown on the plot, the data fit, defined by the pve%, is 0.190 which is not acceptable for analysis. The software package used to perform the statistical analysis (Weibull 4.0) indicated that sample number 1 of batch 1, the brush that failed at a load of 0.196 pound, was an outlier and should be discarded from the data set.

The data was reevaluated after omitting the indicated outlier. The data fit is shown in Figure 2, which in this case, had a pve% of 99.9.

(Note: Other statistical methods were tried including a two parameter Weibull with and without the "outlier." In all cases, the three parameter Weibull provided the best "fit" by a large margin.)

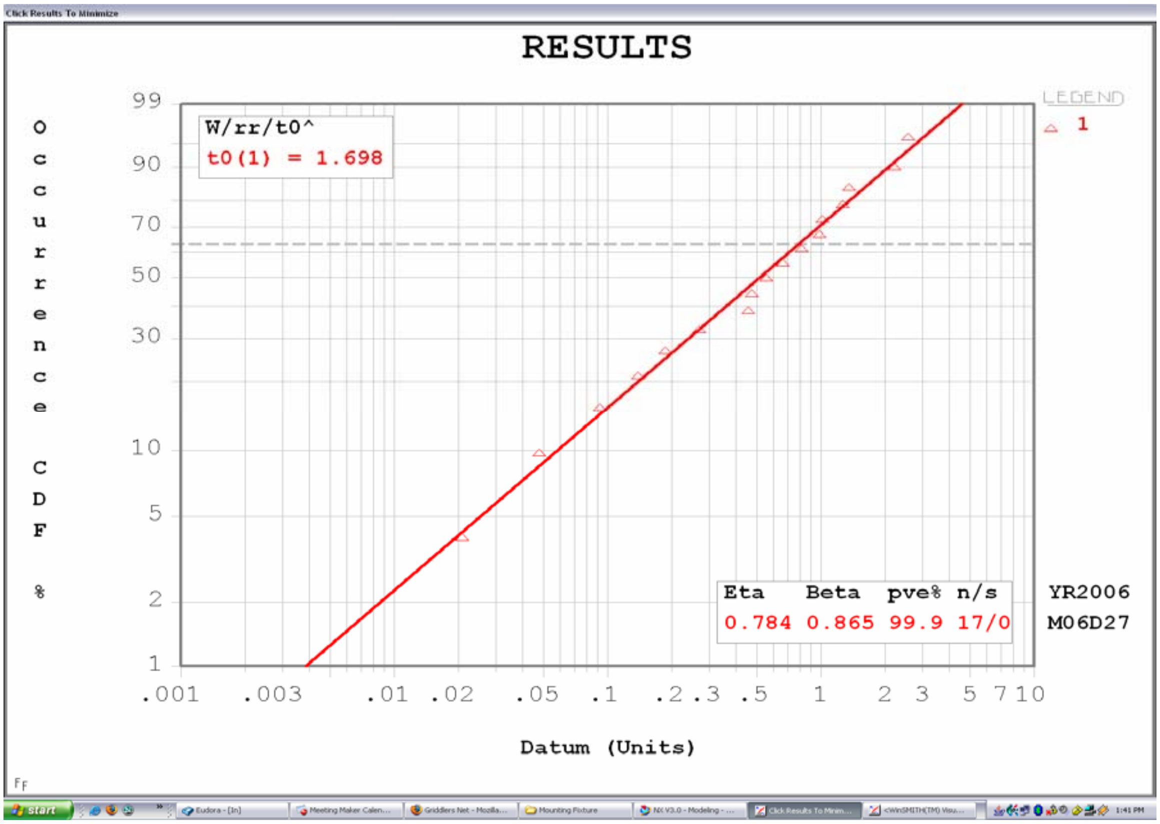


Figure 2. Three Parameter Weibull without Outlier

Once the proper data fit was established (three parameter), the analysis software was used to establish a probability of survival, P_s, based on the following equation:

$$P_s = e^{-\left(\frac{F - F_0}{\eta}\right)^{\beta}}$$

F: Applied load, lbs
F_o: Threshold fracture load (shown as t0 is above plots)
η: Characteristic load
β: Weibull Modulus

Inputting values for F_o, η, and β, generated by the analysis software using both Rank Regression and Likelihood Ratio methods of into the above equation yielded the following results shown in Figure 3.

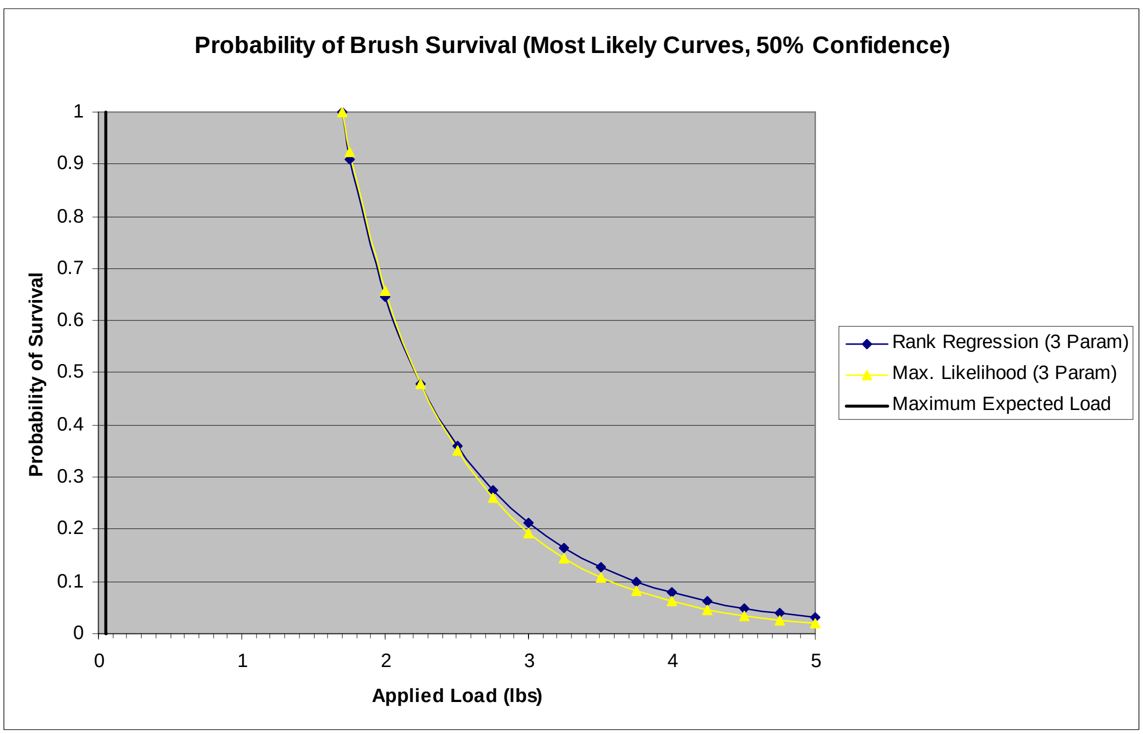


Figure 3. Probability of Survival

In the above plot, the vertical line indicates the maximum expected load a RE020 Brush will be subjected to.

Conclusion

A shown, the predicted load at which failure of a brush will occur is much greater than any expected load the brush will see. Further information pertaining to expected loads can be found in IOM 3550-DN-0647, Load Equivalents on RE020 Motor Brushes.

Appendix E. Load Equivalents on RE020 Motor Brushes

JPL

Jet Propulsion Laboratory
California Institute of Technology

INTEROFFICE MEMORANDUM
Aug. 24, 2006
IOM 3550-DN-0647

TO: **D. Sevilla**

FROM: **D. Noon**

SUBJECT: **Load Equivalents on RE020 Motor Brushes**

Executive Summary

With the exception of pyroshock, all environmental loads would produce negligible loads on the motor brushes. Even the "outlier" weak motor brush in our strength testing program would have a quasi-static capability of 945 g's, comfortably above the 5.5 g rms random acceptance test and 58 g landing loads qualification value.

Calculations indicate that peak accelerations in excess of 200 g's radial or 75 g's axial are necessary before relative brush movement within the motor occurs. Once this threshold of movement is exceeded, there is the possibility of internal impact events, with potential peak loads well in excess of the external excitation… similar in nature to pyroshock. It is not possible presently to estimate these impact load peaks, or to relate such loads to the likelihood of failure.

Introduction

The strength testing performed on motor brushes used a loading method that was simple and repeatable. We would like to relate these strength values to loading events that are actually applied to the motor, i.e. vibe testing, landing loads, and pyroshock.

One critical parameter is brush mass, which is 0.094 grams. We can multiply brush mass by the acceleration to get the force acting on the brush, or vice versa.

There are two directions of loading that must be examined:
1. Radial (relative to motor axis) – tends to force the brush into or away from the commutator
2. Axial – creates a cantilevered load on the brush pivot pin

Radial Loading

This is the loading which corresponds most closely to the motor brush strength tests. While there may be some discrepancy in the applied test load location and the equivalent dynamic-induced load (acts at the brush CG), it is felt that it is accurate enough for these calculations.

Spring Preload
The motor brush is held in contact with the commutator by means of a torsion spring. Previous calculations for MER estimated that ~200 g's acceleration would be necessary to cause loss of contact. Alternatively, we can say that the spring preload is a constant 200 X .094 = 18.8 grams force, or .041 lbf.

Random Vibe
Three levels were applied to MER motors

1. Protoflight (32 motors): used only on the first group, before the qual test had been performed. 9.2g rms, 60 seconds per axis. 9.2 g = .002 lbf rms. Note: this group of motors has been designated non-flight, due to an internal solder joint (Rev A) which was subsequently redesigned.
2. Qualification (4 motors): 4 motors, 7.8 g rms, 120 seconds per axis. 7.8 g = .0016 lbf rms.
3. Acceptance (158 motors): 5.5 g rms, 60 seconds per axis. 5.5 g = .00114 lbf rms.

Landing Loads
Only two groups of motors were subjected to the 58 g peak landing loads (sine burst) environment. Neither group is considered flight: "Rev A" motors, and qualification motors (32 + 4 = 36 total motors).
58 g peak = 0.12 lbf peak

Pyroshock
Normally one uses "SRS" curves when dealing with pyroshock; however, it is the peak accelerations that define brush response. In any case, peak levels are normally well above 200 g's for pyroshock events.

If the acceleration peak from pyroshock is in a direction forcing the brush toward the commutator, the acceleration will add to the spring preload in a straightforward manner.

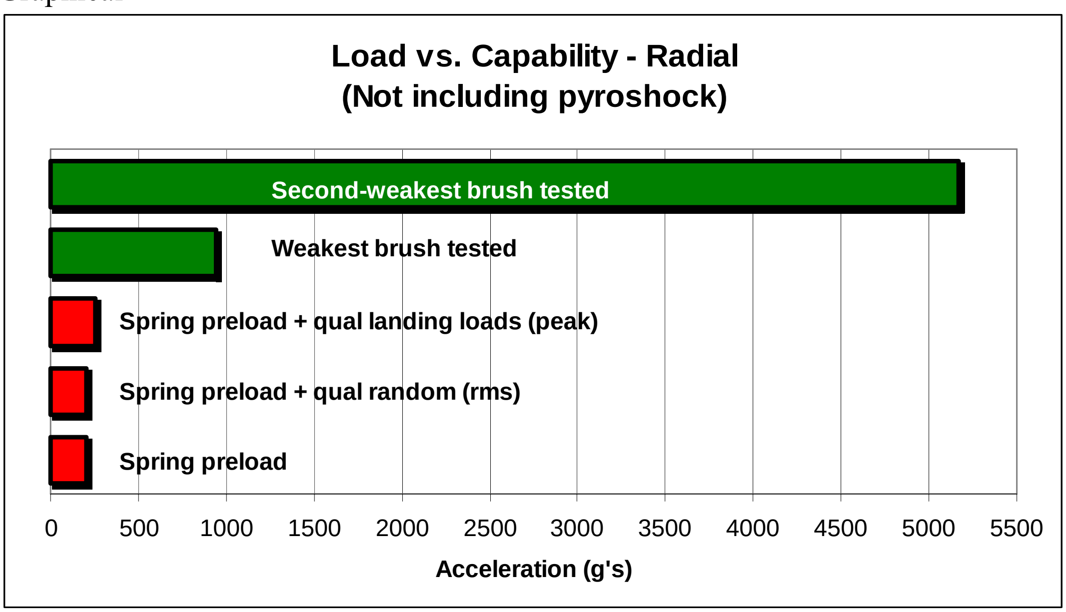
If the pyroshock acceleration is away from the commutator, the brush will lift off of the commutator, impacting back upon the commutator at some later time. Some effort had been expended on modeling the RE25 motor brush dynamics to try to estimate the impact speed and stresses, but there was no convergence of the modeling effort with the actual pyroshock failures (or non-failure). The RE020 has not been modeled in detail. The related calculations that we DO have: if the brush is deflected 45 degrees (slightly greater than the case geometry would allow) and let go, it will impact the commutator at approximately 4.8 meters per second. This test has been performed, with no brush breakage.

Drop Test
One motor was dropped from increasing heights onto a linoleum-covered concrete slab floor. At a drop height of 2 feet, a motor brush broke. Note: it was difficult to get a perfectly flat landing, which would impart maximum impact. Estimating the actual acceleration from this event is not possible.

Tabulated summary

Radial	g's	lb force
Spring Preload	200	0.041
Spring preload + Qual random	207.8	0.043
Spring preload + qual landing loads	258	0.053
Weakest brush found	945	0.196
Second weakest brush	5166	1.070

Graphical



Axial Loading

For accelerations in the axial direction, two sources of restraint come into play:

1. Friction of the motor brush against the commutator
2. Pivot restraint, in a cantilevered bending mode

Friction
Estimated acceleration required for slippage = 65 g's

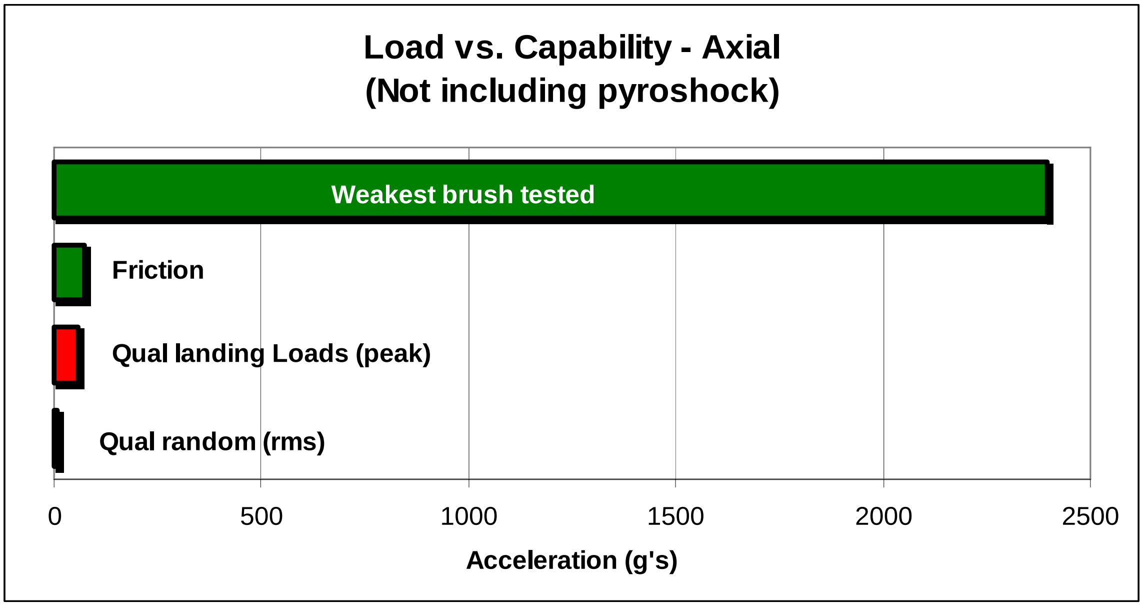
Pivot Restraint
Once friction restraint is overcome, there is a zone of free-play where the clearance is taken up between the pin and the hole in the brush. Wiggling the brush, it appears that this play (as measured at the commutator) is about ±0.5 mm. There would be some impact loading, impossible to estimate.

Testing of motor brush strength in the axial direction has been minimal. In development testing, 3 flight brushes were exposed to an axial force at a distance of 4.3 mm from the pivot pin (approximately the position of the motor shaft). Breaking strength ranged between 225 and 370 grams force (2.2 – 3.6 N), or 2394 – 3936 g's equivalent acceleration. Similar tests were performed by Maxon on 4 brushes, with reported breaking strengths between 7.2 and 9.7 N, equivalent to 7816 – 10530 g's acceleration. It is not known why there is such a large difference between the measurements at JPL and the measurements at Maxon.

Tabulated summary

Axial	g's	lb force
Qual random	7.8	0.002
Qual landing loads	58	0.012
Friction	75	0.016
Minimum measured strength	2394	0.496

Graphical



Summary

With the exception of pyroshock and other impact loads, the brush strengths measured are well in excess of any environmental loads imposed.

Pyroshock normally is quantified in terms of SRS, an RMS energy spectrum which assumes a Q=10 response in the article under test. It is not clear that this adequately measures the damage potential to the brushes. Conceptually, it is the peak (or peaks) of acceleration that are important. If a peak exceeds the quasi-static capability of the brush, there may be immediate damage. If a peak exceeds the spring preload (200 g's) or friction force (75 g's), relative movements within the motor could lead to damaging impacts.

The pyroshock and impact loadings appear to be the most likely source of damage potential, but these loads and their relationship to brush failure have thus far been irreconcilable by analysis.

Cc: Arakaki, Bonitz, Burke, Reed, Shiraishi