

Mars Exploration Rover Potentiometer Problems, Failures and Lessons Learned

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Abstract

During qualification testing of three types of non-wire-wound precision potentiometers for the Mars Exploration Rover, a variety of problems and failures were encountered. This paper will describe some of the more interesting problems, detail their investigations and present their final solutions. The failures were found to be caused by design errors, manufacturing errors, improper handling, test errors, and carelessness. A trend of decreasing total resistance was noted, and a resistance histogram was used to identify an outlier. A gang fixture is described for simultaneously testing multiple pots, and real time X-ray imaging was used extensively to assist in the failure analyses. Lessons learned are provided.

Introduction

On the Mars Exploration Rover (MER), many angular positions required remote monitoring. An incomplete list includes the angular positions of four Steering Actuators (WSA), the azimuth, elevation, elbow, wrist and turret joints on the Instrument Deployment Device (IDD), and the azimuth and elevation axes of the High Gain Antenna Gimbal (HGAG). On the MER Lander, knowledge of the angular position of the three Lander Petals was also required. The MER avionics monitored these angular positions by reading the digital, incremental, rotary, magnetic encoder on each of the fourteen electric motor shaft inputs to these geared mechanisms. In case of encoder failure, or if avionics power and thus stored angular position data was lost, all fourteen angular positions could be determined and tracked via backup precision analog potentiometers (pots) configured to measure the output angles of the WSA, the IDD joints, the HGAG axes and the Lander Petals.

Pots were also used in the MER suspension. The left and right rocker-bogie pivots each had one pot to measure the relative angle between each bogie and its rocker arm, while a third pot in the MER differential measured the relative angle between the left and right rocker arms. In conjunction with a three-axis accelerometer providing the Rover's orientation with respect to a gravity vector, relative angle measurements from these pots allowed the Rover's complete kinematic state to be determined. Though the suspension pots were the sole source for this data, it was deemed non-critical for a nominal mission.

Pots are miniature electromechanical mechanisms and as such must pass a rigorous series of tests to be considered flightworthy. This paper will describe some of the more interesting issues that arose during qualification testing of the MER pots, detail their investigations and present their final solutions. Lessons learned along the way will be pointed out.

Description of Pots

The Lander Petal, Bogie Pivot and Differential pots shared a common design based on MIL-PRF-39023; single-turn rotary pots in a metal cup with a bearing-mounted input shaft. The HGAG and WSA pots were each custom, single-turn rotary units designed to be mounted within their respective actuators, and thus had no bearings of their own.

All pots used on MER were of the precision rotary nonwire-wound (conductive plastic) type. Since the pots described in this paper (Figure 1) were provided by a single vendor, they shared basic design features such as:

- 1) An aluminum alloy "cup" which served as the frame of the pot.

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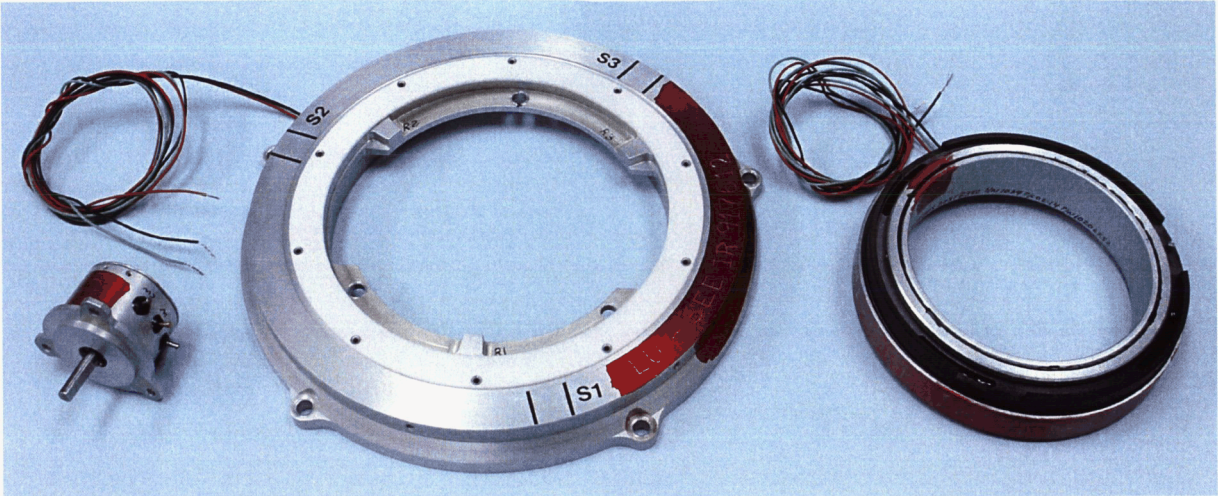


Figure 1. MIL-PRF-39023-style pot, HGAG pot, and WSA pot, from left to right

- 2) A conductive plastic disk bonded to the cup. This disk contains two annular tracks: a $<360^\circ$ resistive track (the resistance element that the wipers rub) and a 360° conductive track (or slip ring) co-molded into the Diallyl Phthalate disk substrate.
- 3) External electrical connection via three brass terminals potted into the cup on the MIL-PRF-39023-style pots, or three 28 AWG pigtailed provided on the WSA and HGAG pots.
- 4) Internal electrical connections made by welding, soldering or bonding with conductive epoxy, and employing solid, flat ribbon wire conductors connecting:
 - a) the end termination junctions of the resistance element to the "CW" and "CCW" input terminals or input pigtailed, and
 - b) the junction on the conductive track (slip ring) to the "W" wiper terminal or wiper pigtail.
- 5) Series connected wipers mounted to, but insulated from, the rotating shaft. Sweeping over both tracks, they pick up the voltage from the resistive track and send it through the conductive track (slip ring) to the wiper terminal. Wipers were comprised of multiple, thin, cantilevered contact fingers made of precious metal alloys with contact forces controlled to approximately 20g.

During calibration, each resistance element was manually trimmed to a specified linearity tolerance by scratching the surface of the conductive plastic disk with a scribe, and/or by placing dots of conductive silver paint on its surface. All resistance elements were $6250 \pm 20\%$ Ohm and rated for 1 watt; all wiper circuits were rated to carry 10 mA. The MER avionics energized the resistance elements with 5 VDC for a power dissipation of <5 mW and drew only 50 nanoAmps through the pot wiper circuits.

Qualification Testing

To expedite matters, the MER project designated one mechanical engineer to be cognizant of all pot technical issues and qualification testing. For validation purposes non-flight Engineering Model (EM) pots were ordered and received well before the flight pots. To reduce cost and lead time, the EM pots were subjected to a reduced set of acceptance tests by the manufacturer. When the EM pots arrived at JPL they were distributed to the end users without careful inspection or electrical testing.

Most of the qualification testing on the flight pots was done by the manufacturer per a JPL-approved Acceptance Test Procedure (ATP). However, since the manufacturer did not have thermal-vacuum test chambers capable of the required -120° to $+110^\circ$ C range, the thermal-vacuum qualification tests were performed at JPL. When the flight pots were received at JPL, each was given a room temperature functional test. First the total resistance of each pot was measured. Then 5 VDC was applied across the input terminals of each MIL-PRF-39023-style pot to energize the resistance element. While its bearing-supported shaft was manually rotated, the output voltage of each pot was plotted on a strip chart recorder.

Since the HGAG and WSA pots had no bearings, each one was placed into a functional test fixture and 5 VDC was applied across its input pigtailed to energize the resistance element. While its rotor was manually rotated, the wiper or output voltage of each pot was plotted on a strip chart recorder. All pots were then placed in a vacuum chamber. Once evacuated the pots were subjected to three thermal cycles of -120°C to $+110^{\circ}\text{C}$. Finally, each flight pot was given a second room temperature functional test.

During the two functional tests, problems were noted with the following flight pots: MIL-PRF-39023-Style S/N's 1035 and 1041, HGAG Pot S/N 1017 and WSA Pot S/N 1039 (Note: all S/N's were randomly assigned by JPL). JPL Problem / Failure Reports (PFR) were initiated to describe the test failures. Shortly after the PFR's were initiated the cognizant engineer for the MER pots left JPL and I assumed her role. Though I was experienced in the construction, cleaning and use of non-flight pots, I had no knowledge of the MER pot effort prior to my taking it over. The remaining three sections of this paper discuss each of the failure investigations and present lessons learned.

MIL-PRF-39023-Style Pots

The Initial Problem

Functional testing of the MIL-PRF-39023-style pots before and after the three thermal cycles revealed:

- a) S/N 1035's total resistance varied from approximately 5130 to 5720 Ohms as the shaft was turned, when nominally the value should have remained constant. In addition, there was an open circuit through the wiper terminal for all shaft positions, and
- b) S/N 1041 showed an open circuit through the wiper terminal for shaft positions that should have corresponded to voltage ratios between 0.0 and 0.1.

After duplicating the original functional test setup and now taking the proper precautions (see Lessons 1 - 6), the problems were verified, the out-of-spec electrical performance was characterized and a "scratchy, detent" feel was noted as the shafts were rotated.

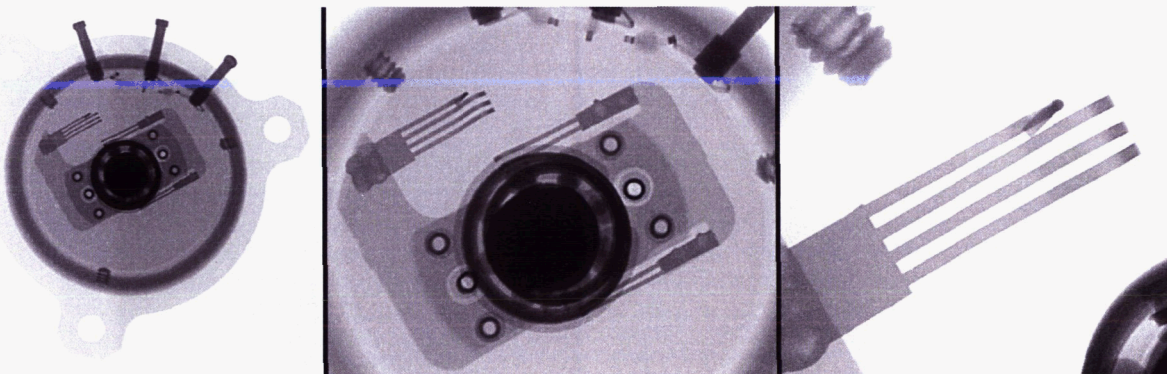


Figure 2. X-ray images of the S/N 1041 pot at increasing magnification show wiper damage

FeinFocus real-time X-ray images of the pots revealed wiper damage (Figure 2). Subsequent disassembly of S/N's 1035 and 1041 revealed that the resistance element wiper, slip-ring wiper and the conductive plastic disk were all damaged due to high current and/or arcing (Figure 3).

The wipers showed arc scarring: pitting coupled with discoloration and warping due to overheating (Figure 3). The end of one S/N 1035 wiper finger was burned off and embedded in its conductive plastic disk. The disks were damaged in two places: a) heavy arcing damage to the triangular shaped junction between the "CCW" end of the resistance element and the mound of conductive epoxy connecting the "CCW" terminal's flat ribbon wire, and b) light arcing damage to the slip-ring portion of the disk where one of the two slip-ring wipers was located. The carbonized shell of a "bubble" was observed across the wiper tracks on S/N 1035's conductive plastic disk where vaporized disk substrate "puffed up" the overheated top layers. There was a trough across the wiper tracks in S/N 1041's conductive plastic disk where the substrate was vaporized away.

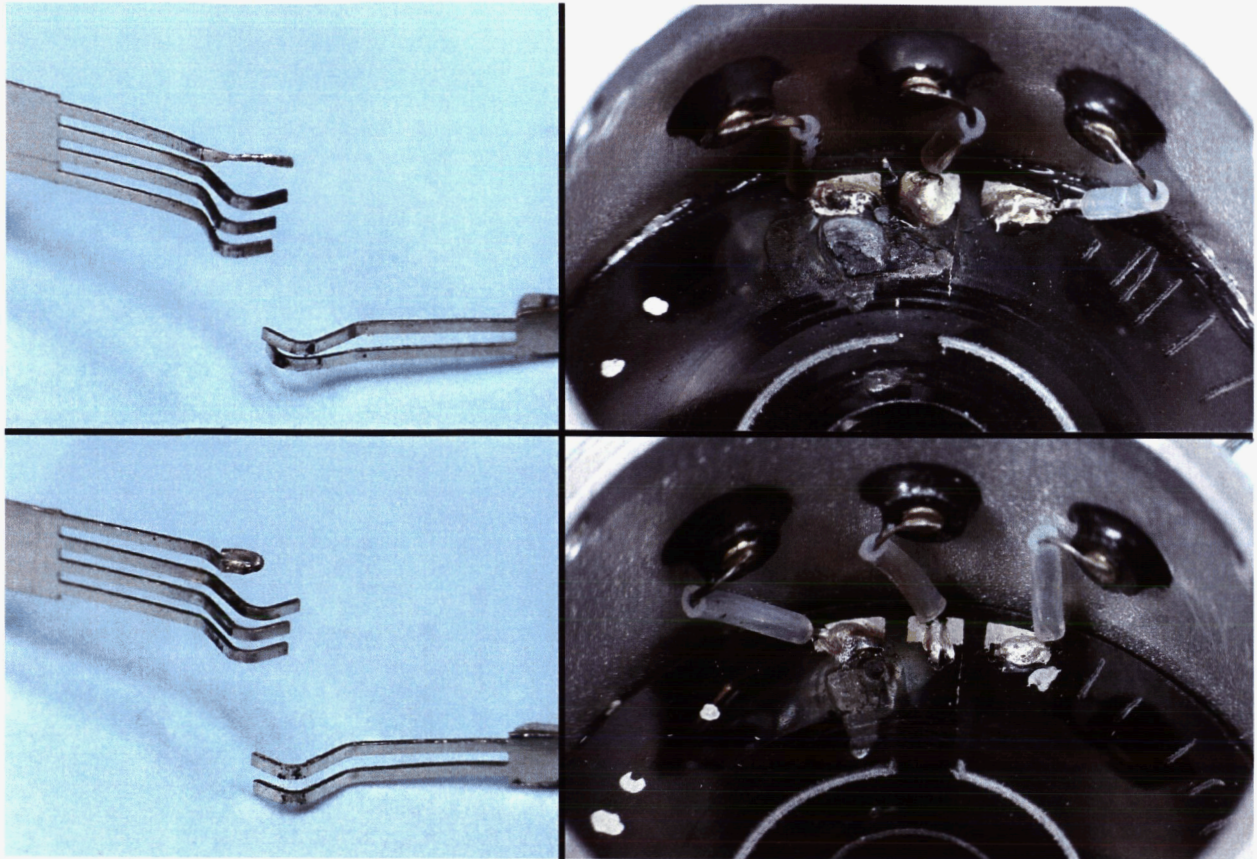


Figure 3. Arc damage to fingers on wipers, and to conductive plastic disks on S/N 1035 and 1041

Immediately after documenting the extensive damage in these pots, I began investigating probable causes. As I was not present during the original testing, I had to perform some detective work. I discovered that the manufacturer's rating for the current through the wiper circuit, though never specified in any of the MER pot specs, was only 10 mA. Whenever a wiper was positioned near the "CCW" end of the resistance element, a low resistance ($\ll 500$ Ohms) circuit existed between the "CCW" and "W" terminals (Figure 4). If 5 VDC was applied between the "CCW" and "W" terminals when the wiper was positioned near the "CCW" end of the resistance element, a current well in excess of the manufacturer's rating would have flowed through the wiper circuit, damaging the pot.

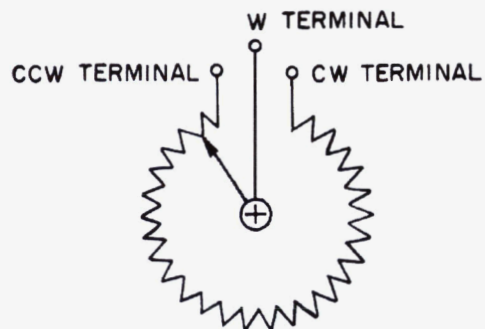


Figure 4. The wiper position shown forms a low resistance circuit between CCW and W terminals

The procedure that covered the functional testing of these pots read:

Set multimeter to 10 kOhm - 20 kOhm range...

Perform the following steps for each potentiometer:

1. Remove each potentiometer from its shipping container.
2. Record the resistance from the CW to the CCW terminals in the table at the end of this procedure. Resistance should be between 5 kOhm to 7.5 kOhm.
3. Remove lead from CW terminal and reattach lead onto W terminal.
4. Using a chart recorder, power supply set to 5V, and multi-meter, rotate the rotor of each potentiometer through its entire electrical range by hand. Attempt to rotate the rotor at a constant rate. Look for discontinuities or noise in the signal. Record the potentiometer part and serial number on each strip chart, and append the strip charts to this procedure.
5. Replace each potentiometer into its shipping container.

No electrical schematic was given and no polarities were mentioned. Note that step 3 left the pot's "CCW" and "W" terminals connected to test leads and implied rather than mandated the switching of the multimeter from the "Ohms" to "DCV" range. Step 4 connected a power supply but did not specify how, and though the power supply could deliver 3 amps, there was no instruction to set a current limit. Then rotating the pot ensured that the wiper would pass over the "CCW" end of the resistance element.

The same set-up was used to test all pots. Had the power supply been wired across every pot's "CCW" and "W" terminals, all pots would have been damaged identically. However, the first seven pots tested using this set-up passed. S/N 1035 was the eighth pot tested but the first one damaged. S/N 1041 was the twenty-sixth pot tested, but only the second one damaged. Therefore, it can be concluded that nominally the power supply and instrumentation were wired correctly and that the power supply was not intentionally connected across every pot's "CCW" and "W" terminals.

Close examination of the internal damage indicated that the wipers were stationary when the problem occurred. Note that Pomona Electronics brand "Minigrabber" test clips were used to connect to the pot terminals (Figure 5). When depressed, a beryllium-copper hook projects from the end of these test clips. As the procedure does not mention turning off the power supply outputs, the pots were likely hooked up to live (powered) test clips. The terminals on the MIL-PRF-39023 style pots are only 6mm apart. When attaching the powered clip meant for the "CW" terminal, it would have been very easy to bump the "W" terminal with the metal hook, or even clip it to the "W" terminal outright. If the wiper happened to be positioned near the "CCW" end of the resistance element, a high current could have flowed through the wiper circuit and caused the damage observed.

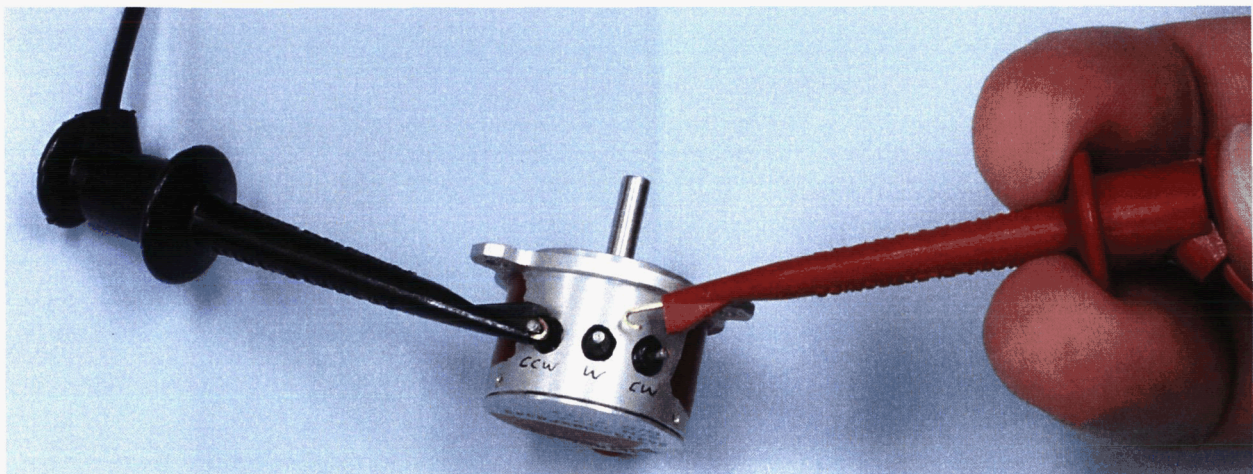


Figure 5. The live, exposed hook on the test clip is a danger to pots with closely spaced terminals

How near is "near"? Ohm's Law says that at 5 VDC, 10 mA will flow through a resistance of 500 Ohms. If the resistance between the "CCW" and "W" terminals varies from 0 Ohms to the full 6250 Ohms over the 320 degree electrical range, then a current in excess of the wiper circuit's 10 mA rating would flow if the wiper was within $320 * (500 / 6250) = 25$ degrees of the "CCW" end of the resistance element. If the shafts were in purely random orientations when connected, one would expect $25 / 360 = 7\%$ of the pots to be damaged. Of the 31 MIL-PRF-39023-style pots connected, two (or 6.5%) were damaged.

Based on the preceding failure analysis, this problem was attributed to test error due to a procedure fault. Pot S/N's 1035 and 1041 were scrapped. The pot specification and drawings were revised to include the 10 mA rating for the wiper circuit. The following lessons were learned:

LESSON 1. Be aware of low resistance circuits which exist between the "CCW" and "W" terminals when the wiper is positioned near the "CCW" end of the resistance element, as well as between the "CW" and "W" terminals when the wiper is positioned near the "CW" end of the resistance element. Warn of these conditions in the test procedure.

LESSON 2. In the pot specification and on the pot drawing, clearly state the current rating for the wiper circuit.

LESSON 3. Based on a fraction of this rating, set current limits on all power supplies used in pot testing.

LESSON 4. Provide an electrical schematic for connecting wires, and write detailed procedure steps.

LESSON 5. Use insulated test clips to connect to terminals that are in close proximity to each other. Alternately, solder hook-up wires to the terminals and connect leads to the wires.

LESSON 6. Turn off the power supply outputs when connecting test leads - do not hook live (powered) test leads to flight hardware.

LESSON 7. Before they are allowed to play with electricity on the job, make sure all mechanical engineers and technicians can pass the "flashlight test" (hand them a D-cell, a single piece of wire and a flashlight bulb and ask them to enlighten you).

The Ripple Effect

It would have been great to end the investigation there. However, every flight pot that underwent functional testing per the quoted procedure was potentially damaged and had to be proven flightworthy all over again. It was not possible to tell from the X-ray images if the conductive plastic disk was damaged, therefore the only sure way to prove that a pot was undamaged was to remove its lid and conduct a visual inspection using magnification. Each lid was retained by three equally spaced radial set screws threaded into the wall of the cup which were tightened against the bottom of a circumferential groove machined in the lid. Loosening these setscrews should have allowed the lid to be removed. But disassembly of S/N's 1035 and 1041 showed that it wasn't quite so easy:

a) one of the shaft bearings was mounted in the lid. Removing the lid thus represented major disassembly, unloading the preloaded wipers and possibly invalidating all the qualification testing performed to date, and

b) the set screws used to retain the lid had no secondary locking feature, so the original cognizant engineer required that the manufacturer apply Solithane to the set screws to bond them in. The Solithane used by the manufacturer had wicked into the circumferential groove and effectively bonded the lids to the cups. Removing the lids would contaminate the wipers, tracks and bearings with Solithane debris, requiring complete disassembly for cleaning and re-lubricating.

Time constraints necessitated an alternative though admittedly less rigorous approach. It was decided that the remaining flight pots would all be screened for any of the characteristics observed in the failed S/N's 1035 and 1041, namely:

a) out-of-spec electrical performance by electrical functional testing at room temperature, at the operating temperature extremes of -75° C and $+70^{\circ}$ C, and again at room temperature, and

b) any "scratchy, detent" feel as each shaft was rotated.

A complete functional test required rotating each pot while monitoring its wiper terminal voltage. This test was quickly and easily done at room temperature, but having to test 28 pots at -75°C and $+70^{\circ}\text{C}$ in a minimum amount of time required a different approach. A gang fixture was designed and constructed with a stationary plate that supported up to 36 MIL-PRF-39023-style pots (Figure 6). A driveshaft turned a central crank arm which rotated a second plate eccentrically. The eccentric rotation of the second plate was converted into rotation of the individual pots by a crank arm on each pot shaft.

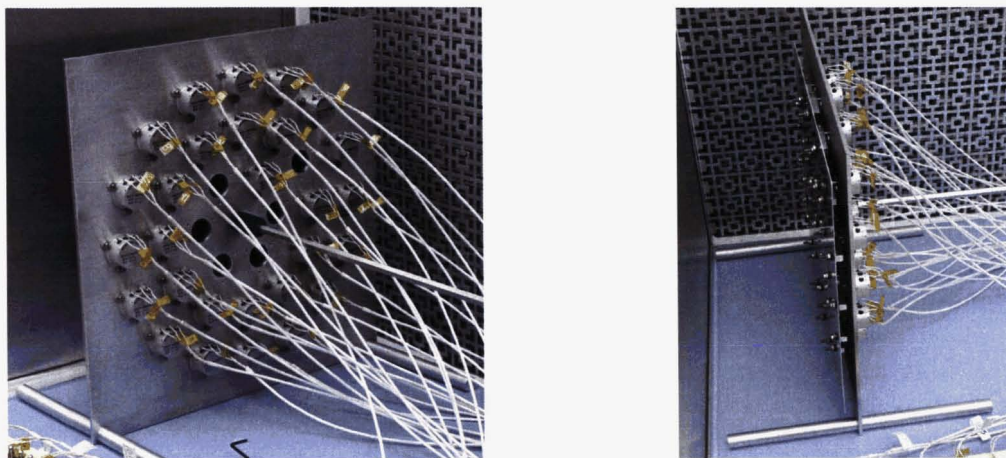


Figure 6. Two views of gang fixture with 28 pots installed, before being placed in chamber

This gang fixture was set up in a dry nitrogen purged thermal test chamber employing electrical heating and liquid nitrogen cooling. The driveshaft passed through an opening in the chamber wall to a gearmotor. With this set-up, electrical performance was rapidly verified at the temperature extremes in both the CW and CCW directions. The following lesson was learned:

LESSON 8. Don't put all your eggs in one basket. Trying out a new test procedure on all the *irreplaceable flight pots in one batch is risky*. It is a great deal of work to recertify potentially compromised pots for flight. Instead prove out the test procedure with a few disposable EM pots. Complete the testing and data analysis, then revise the procedure with lessons learned before applying it to any flight pots.

The Ripple Effect, Part II

The next step was to check for any "scratchy, detent" feel as each pot shaft was rotated. This was a very delicate task as the torque required to rotate each ball-bearing supported shaft was at most a couple of millinewton-meters. With no sensitive torquemeters available, I turned off the laminar flow benches in the clean room to eliminate their noise and vibration, turned off most of the lights to get rid of the powerline buzz, and ripped the thumb and index finger off my right glove. One by one I took each pot in my hands and rotated the shaft back and forth with my bare fingers, eyes closed and concentrating. Soon I was writing another PFR to document the very weak detent that was felt as the shaft of:

- a) S/N 1027 was rotated by hand through the ~ 190 degree CW shaft orientation, and
- b) S/N's 1021 and 1036 were rotated by hand through the ~ 240 degree CW shaft orientation

In each case the shaft orientation where the detent was felt did not change, even after many shaft rotations; clearly it was not caused by a bad ball in the bearing or a bad inner race. The detent on S/N 1027 occurred at the ~ 190 degree CW shaft orientation which placed the wiper in the electrical dead zone of the pot so damage from high current should not have been a problem. The detents on S/N 1021 and 1036 occur at the ~ 240 degree CW shaft orientation which placed the wiper far enough away from the "CCW" end of the resistance element that damage from high current should not have been possible. Functional testing at room temperature, -75°C and $+70^{\circ}\text{C}$ had already verified the required electrical performance for these three pots. X-ray images revealed no macroscopic wiper damage, though it was not possible to tell from the X-ray images if the conductive plastic disk was damaged. How could I be

feeling what was supposed to be a symptom of arc damage, when arc damage was absent and/or impossible? And why did these detents feel much weaker than those on S/N's 1035 and 1041? This new problem had me stumped until the shafts were rotated to the detent positions and the pots were placed back in the FeinFocus X-ray machine.

Close examination of the X-ray images showed that at the ~190 degree shaft position on S/N 1027, the wiper bracket on the shaft passed very close to the flat ribbon wire connecting the "CW" terminal to the resistance element. On most pots, the flat ribbon wires were bent towards the case immediately upon exiting the hole in the conductive plastic disk. However, on S/N 1027, the "CW" flat ribbon wire was not bent towards the case, leaving it closer to the rotating parts than usual. Careful examination of X-ray images of S/N 1027 show that the wiper bracket rubbed the insulating Teflon sleeve on this flat ribbon wire. This rubbing interference was consistent with all observations listed above, represented a new discovery, and was declared to be the cause of the detent.

The flat ribbon wires were welded to the ends of the terminals inside the pot case. However, from one pot to another there was no uniformity to the angle or direction that each flat ribbon wire pointed as it left its terminal (Figure 3). On S/N 1027, the "CW" flat ribbon wire left the "CW" terminal in a direction pointing away from its termination in the conductive plastic disk. Therefore, the flat ribbon wire had to be bent back upon itself in order to be inserted in its hole. Doubling the flat ribbon wire back on itself used up some of its finite length, and was likely why the "CW" flat ribbon wire wasn't bent towards the case when it exited its hole; there simply wasn't enough length available.

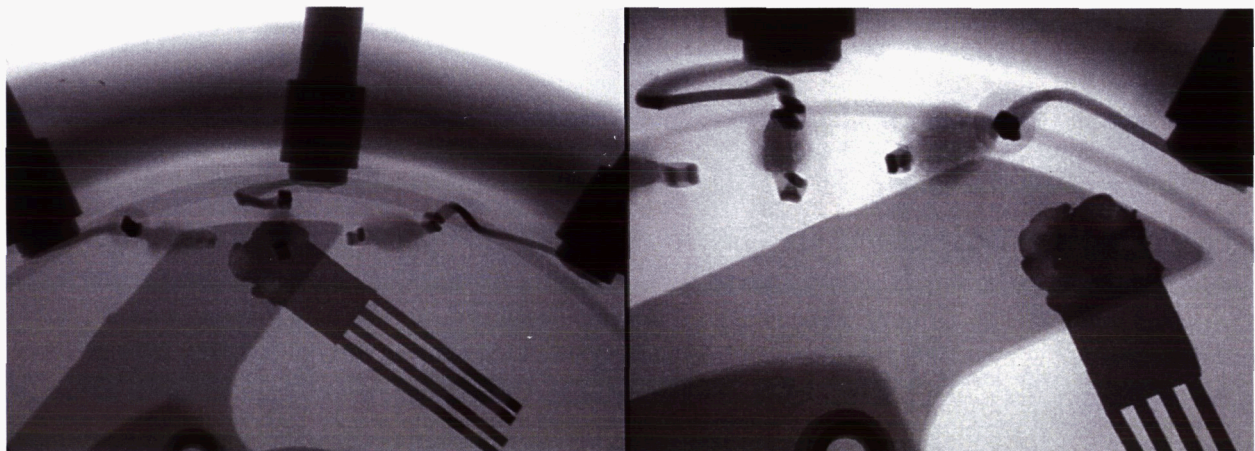


Figure 7. X-ray images of pots show cause of detent: interfering Teflon sleeve on flat ribbon wire

X-ray images of S/N's 1021 and 1036 (Figure 7) also showed that their wiper brackets rubbed the insulating Teflon sleeves on their flat ribbon wires. This rubbing interference was consistent with all observations listed above, and was declared to be the source of their detents as well.

Note that these three pots were never disassembled for direct visual verification because:

- a) the cover (lid) was glued on and prying open this lid would create debris which could contaminate the bearings and resistance element, and
- b) removing the lid with its integral bearing allows the shaft to tilt in the single bearing in the cup, preventing accurate checks of the clearances between the wiper bracket and Teflon sleeving, and
- c) since the detent-causing interference could be clearly seen from the X-ray images, it was not necessary to de-lid the pots.

The three pots had been subjected to 5400 revs during testing by the manufacturer and then received another 300 revs at JPL during testing on the gang fixture. The Teflon sleeve had been rubbed by the metal wiper bracket 5700 times, deflecting the flat ribbon wire each time. The number of rubs that cause failure of the flat ribbon wire was unknown, so no prediction could be made as to how much life remained.

Based on the preceding failure analysis, this problem was attributed to manufacturing error due to a faulty production process. S/N's 1021, 1027 and 1036 were labeled "Limited Use (Non-Flight Part)" and were not used for flight.

Except for S/N 1021, 1027 and 1036, all the other pots passed this screening process. Absence of any detent feel means only that the conductive plastic disk/wiper/bearings were not damaged and that there was some clearance between the rotating and stationary parts at room temperature. It was not a measure of how much clearance existed, nor was it a guarantee that clearance existed over the entire operating temperature range. However, it would have been impractical to check for detents at other than room temperature since detecting them requires a very sensitive touch in a quiet room with no vibration. This risk was accepted and the remaining pots were approved for flight use. Lessons learned include:

LESSON 9. Sometimes you have to take off the gloves. In a quiet, vibration-free room, extremely subtle mechanical effects can be felt reliably only through bare skin contact.

LESSON 10. An X-ray inspection machine with real-time imaging capabilities is an extremely valuable tool for performing non-destructive evaluation on assemblies that are sealed or for which disassembly would affect internal clearances or invalidate qualification testing already conducted.

LESSON 11. Interferences within the MIL-PRF-39023-style pots are possible. The pot manufacturer should:

- a) individually specify and inspect the angle or direction that the flat ribbon wire points as it leaves each of the three terminals. The angle should be chosen to provide a direct route to each flat ribbon wire's respective hole in the conductive plastic disk.
- b) specify and inspect that each flat ribbon wire must be bent towards the case immediately upon exiting the hole in the conductive plastic disk. This would ensure that the flat ribbon wires will be against the inner wall of the case and maximize the clearance between the rotating and stationary parts. A cutaway cover or functional gage could be designed that would permit inspection and verification of a minimum acceptable clearance.
- c) investigate a shorter wiper bracket or an alternative "lower profile" method of insulating the flat ribbon wire, to provide more clearance between the rotating and stationary parts.

Set Screwed

While concentrating all my tactile attention on the flight pot shafts rotating between my fingers, I noticed that many were not smooth. Close examination revealed deep impressions with raised edges that made each precision 3.170 +0.000/-0.005-mm-diameter shaft reminiscent of a bastard-cut round file. Some EM pots showed this damage as well. During testing per the ATP, the manufacturer must have used a breaker bar to repeatedly tighten R_c 52 hardened steel cup-point set screws into the R_b 82 annealed 303 stainless steel pot shafts. To correct this damage, the affected pots needed to have their shafts deburred with an India oilstone before I could deliver them to their end users. Deburring generates metal chips and abrasive fines, so to prevent contamination each pot was bagged and taped to expose just its shaft for deburring. After deburring was complete, the shafts were cleaned and the bags removed. The following lesson was learned:

LESSON 12. If for testing purposes EM pots are ordered and received long before the flight pots, then immediately upon receipt the EM pots should be carefully inspected and the manufacturer should be contacted about quality issues like precision shafts marred by set screws. Before fabricating the flight pots the manufacturer should be instructed to tighten setscrews against the shaft's machined flat and not its precision outer diameter, to properly control setscrew torques, to use brass or nylon tipped setscrews, and/or to switch to non-setscrew style couplings on their test equipment.

Observed Trends

Continuing the investigation, the total resistance measurements captured my attention next. A plot of the total resistance of the MIL-PRF-39023-style pots showed it to be decreasing with either time and/or thermal cycles. The plot in Figure 8 shows the history of these total resistance measurements with each line representing a different serial number pot. The spec for these pots was 6250 Ohms \pm 20%, or 5000 to 7500 Ohms. There was minimal drift measured by the pot manufacturer before and after their thermal

testing (measurements #1 and 2), but significant drift was measured after each JPL thermal test (measurements #3 - 6). Discussion with the original cognizant engineer responsible for measurements #3 and 4 revealed that the ohmmeter was never zeroed, which would have put a constant offset error on all values measured. If that offset had been approximately -170 Ohms, there would be a uniform downward trend across nearly all measurements. I became concerned that if this trend continued, the daily thermal cycles experienced by the Rovers might cause the total resistance of the pots to drift out of spec.

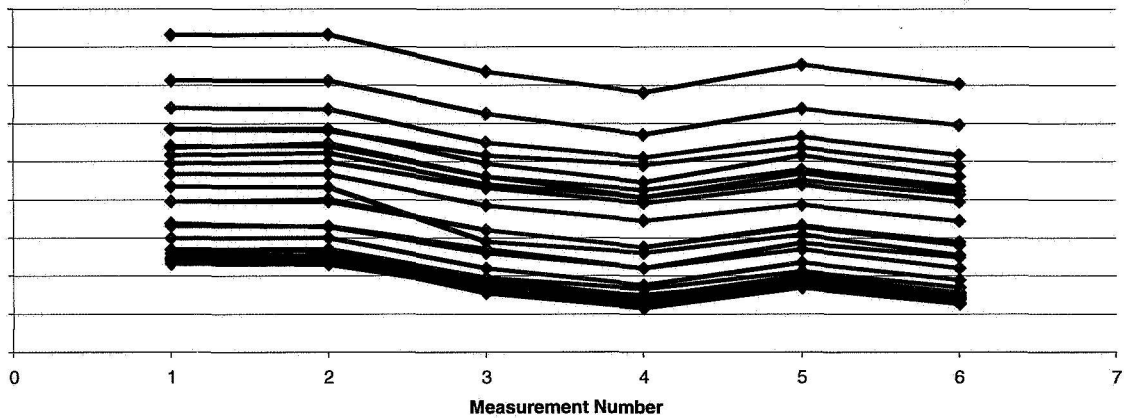


Figure 8. Total Resistance measurement history

When notified of this observation the pot manufacturer said that it was typical for the total resistance of a conductive plastic pot to change after thermal cycling. The mechanism was explained as follows: conductive plastic is made of carbon particles in an insulating matrix, co-cured at 160° C (and rated for operation up to 125° C). Thermal cycles change the insulating matrix on a microscopic level, allowing better conductivity between the carbon particles. Macroscopically these changes appear as a drop in the total resistance. The manufacturer said that as the number of thermal cycles builds, the rate at which the resistance drops will decrease and the resistance will eventually stabilize. The scratches and drops of silver paint used to linearize the pot have an effect on the rate at which the resistance stabilizes. The manufacturer assured me that the resistance changes would be uniform throughout the length of the resistance element and that the pot's linearity would not be affected by changes in the total resistance.

Interestingly enough, the pot manufacturer also said that just leaving the pot on a shelf for a time after thermal cycling will cause the pot to recover some, but not all, of the resistance loss which occurs during thermal cycling. They called this a "memory" effect.

LESSON 13. To gain insight, plot every measured quantity and look for trends. If a measurement is worth recording, it is worth plotting.

LESSON 14. Calibrate test equipment before using it on flight hardware. The data is only as good as the calibrations; i.e., always "zero" an ohmmeter before measuring any resistance.

LESSON 15. Manufacturing considerations and physical mechanisms are the reason a precision pot has the relatively loose tolerance of $\pm 20\%$ on its total resistance.

Add Vent Holes, Then Glue Them Shut

MIL-PRF-39023-style pot cups trap air so the MER Environmental Requirements Engineer requested a venting analysis. I did some digging and found that during a design review early in the procurement process, the original cognizant engineer had requested that a vent hole be added, so the manufacturer drilled one in the cup between the set screws that hold the lid on. Unfortunately, the original cognizant engineer had also requested that a Solithane mixture be applied to the set screws to lock them in place. When this Solithane mixture wicked into the circumferential groove and effectively bonded the lids to the cups, it also blocked the vent path leading to the drilled vent hole. The only vent path left was the one through the shaft bearing which is undesirable because vented air often carries contamination that can become lodged in a bearing.

LESSON 16. When a design uses one feature for multiple purposes (like the circumferential groove in the lid which was used both to retain the lid and to provide a labyrinthine path for venting), make sure all the effects of even the smallest design change are well understood before approving it.

Turning Gold Into Base Metals

Prior to delivering the pots to the end users I noticed that the original cognizant engineer ordered the MIL-PRF-39023 pots manufactured to a drawing which specifies that its solder terminals are made from brass which has first been silver plated, and then very thinly gold plated.

JPL's internal requirements state that gold shall not be used as a surface finish for soldering, so I instructed the end users of the MIL-PRF-39023-style pots to "degold" the terminals before soldering.

LESSON 17. Soldering to gold can form brittle intermetallic compounds that can crack under thermal cycling. Gold plated conductors must have their gold plating removed by immersion in a designated solder pot, then tinned using the same processes in a different solder pot. Alternatively, gold plated leads must be tinned twice with solder wire, wicking off the solder in the first tinning to remove the gold, then tinning again.

Trust Nobody With Your Flight Hardware

About this time MER's Deputy Mission Assurance Manager requested a private meeting to better understand the pot details described in the PFR's. Afterward this manager asked to borrow several of the pots that had been written up, and I foolishly obliged. When I asked for my pots back, S/N 1036 could not be found: Mission Assurance had lost my flight hardware!

LESSON 18. When cognizant of flight hardware, especially small hardware, never let it out of your sight, and never, ever lend it to management.

HGAG Pots

Functional testing of the HGAG pots before and after the three thermal cycles revealed that on S/N 1017 the total resistance varied from approximately 5440 to 6190 Ohm as the rotor was rotated. The total resistances of the other HGAG pots tested did not vary with rotation angle. Nominally the total resistance should remain constant.

After duplicating the original functional test setup and now taking the proper precautions (see Lessons 1 - 6), the problem was verified.

Next the build documentation was examined to determine if it held any clues to this anomaly. The pot manufacturer's ATP describes the resistance check, but does not mention rotating the rotor, nor does it specify that the total resistance must not vary with rotor angle. The spec only called for a total resistance of 6250 Ohms \pm 20%. The in-process data sheet filled out by the pot manufacturer listed the total resistance as 6046 Ohms. After environmental testing, the in-process data sheet listed the total resistance as 6121 Ohms. 6121 Ohms represented a 75-Ohm increase which was not in keeping with the rest of the pots in that lot which showed total resistance changes of no more than 5 Ohms. Random rotor angles during total resistance measurement explained the 75 Ohm change, and indicated that this problem may have been inherent at assembly.

S/N 1017 was still a flight pot, so I was in no rush to tear it apart. Besides, FeinFocus X-ray images of S/N 1017 revealed no internal damage.

Instead I elected to do more testing. The pot was powered with 1.0 VDC across the input wires and the wiper voltage was measured and recorded as the rotor was rotated through 360 degrees in 5 degree increments. The wiper voltage was indeed the required linear function of rotor angle. Next the total resistance was measured and recorded as the rotor was rotated through 360 degrees in 5 degree increments. The total resistance was a smoothly decreasing function of rotor angle (Figure 9).

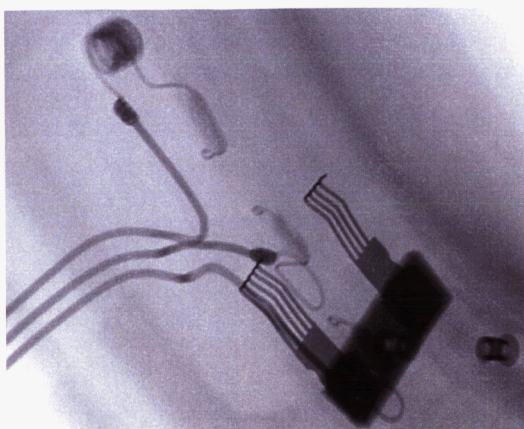


Figure 9. X-ray image of undamaged wiper and slip ring brushes in HGAG pot

After plotting and examining the data, I hypothesized that a high resistance leakage path between the “CCW” end termination of the resistance element and the slip ring could explain the anomaly. A schematic of a pot with an internal leakage resistance was drawn (Figure 10) and an equivalent resistance equation was written as a function of shaft angle. This mathematical model was iterated with different values of leakage resistance until the model predictions matched the measured total resistance data. Note that the 51.9 kOhm leakage resistance found in this way was 8.3 times the pot's nominal total resistance.

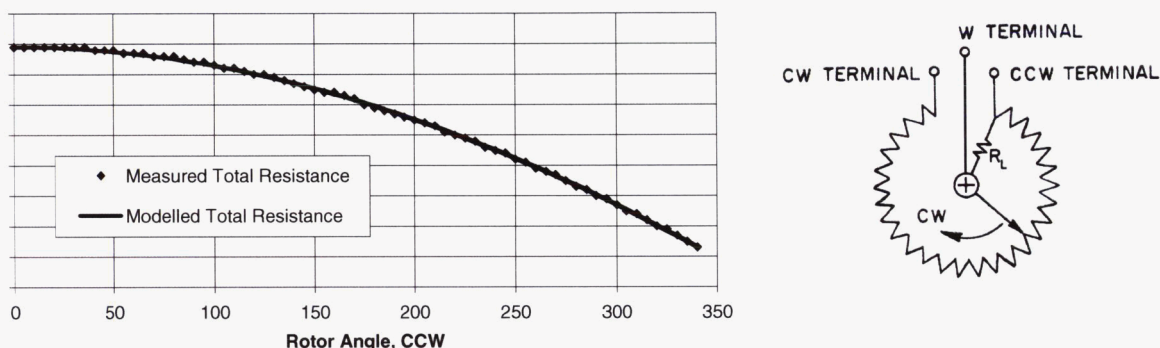


Figure 10. Measurements match model of HGAG pot with internal leakage resistance $R_L = 51$ kOhm

The prediction of the model fits the data extremely well, supporting the hypothesis. The extremely linear output of this pot supports the conclusion that this leakage resistance was present all along but never discovered (because per a strict reading of the ATP instructions, no one was looking for it). Any non-linearity caused by the leakage resistance was likely removed by adding scratches and/or drops of silver paint when the pot's linearity was adjusted by the manufacturer.

True confirmation of the hypothesis requires direct measurement and so the pot was disassembled by removing the rotor from the stator. In this condition the leakage resistance could be accurately measured because the slip ring and the resistance element were no longer bridged by the brushes. With the pot disassembled, the leakage resistance measured 51.4 kOhms to the “CCW” lead, and 57.6 kOhms to the “CW” lead. Note that $57.6 - 51.4 = 6.2$ kOhm, the nominal total resistance.

The resistance element showed a very large number of linearizing marks, with all the silver paint dots grouped in the middle of the element and all the scratches at the ends near the junctions; exactly what one would expect if the pot had been adjusted to get rid of a manufactured-in leakage resistance.

It is reasonable to ask what caused the leakage resistance. There was a concern that it could have formed from conductive debris worn off the surface of the resistance element or slip ring by a rough wiper,

and scattered between them. However that proposed mechanism was eliminated when upon disassembly the resistance element and slip ring showed no signs of wear, scraping or dusting.

The conductive plastic disk was made of carbon particles in an insulating matrix, co-cured at 160° C. It is believed that if some conductive carbon particles in the junction area were displaced from the resistance element and co-cured in place, a high resistance leakage path between the element and the slip ring would have resulted.

While the discovery of the varying total resistance was significant, S/N 1017 has always been within tolerance. Testing verified its linearity, and though it varied, the total resistance was within the $6250 \pm 20\%$ (5000 - 7500) Ohm allowable range. Of course, this leakage resistance does waste a bit of power.

Based on the preceding failure analysis, this problem was attributed to manufacturing error due to a faulty production process. Pot S/N 1017 was labeled "Limited Use (Non-Flight Part)" and was not used for flight.

LESSON 19. Being within tolerance does not mean a pot is problem free.

LESSON 20. Unique behavior is always worth investigating until it is understood, to make sure that the problem does not affect other pots in the lot.

WSA Pots

During functional testing of the WSA pots before the three thermal cycles, the total resistance of WSA Potentiometer S/N 1039 measured 7400 Ohms. After the three thermal cycles, the total resistance dropped to 6900 Ohms. Compared to the other WSA pots in the lot, this change was a full order of magnitude larger than expected.

After duplicating the original functional test setup and now taking the proper precautions (see Lessons 1 - 6), the problem was verified.

Next the build documentation was examined to see if it held any clues to this anomaly. The spec called for a total resistance of 6250 Ohms $\pm 20\%$. The in-process data sheet filled out by the pot manufacturer listed the total resistance as 7391 Ohms. After environmental testing, the in-process data sheet listed the total resistance as 7404 Ohm. While S/N 1039 was in spec, all the other WSA potentiometers supplied to JPL had much lower total resistances. A histogram of WSA total resistance values (Figure 11) clearly shows S/N 1039 to be an outlier.

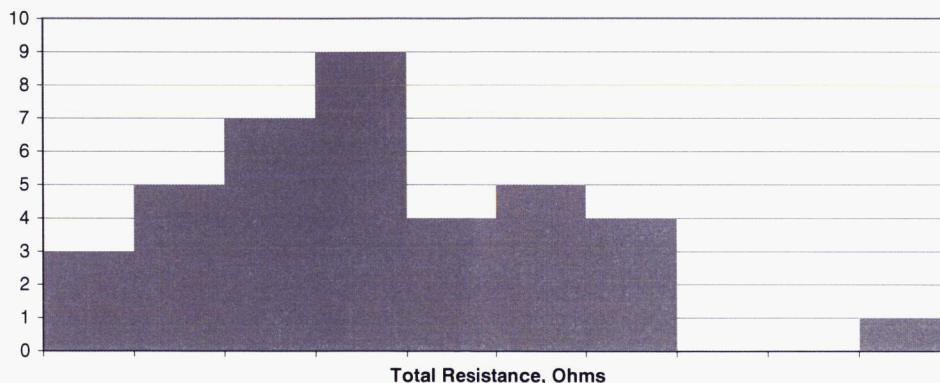


Figure 11. Histogram of Total Resistance values showing the lone outlier, S/N 1039

S/N 1039 was still a flight pot, so I was in no rush to tear it apart. Besides, FeinFocus X-ray images of S/N 1039 revealed no internal damage.

Instead I elected to do more testing. The pot was powered with 1.0 VDC across the input wires and the wiper voltage was measured and recorded as the rotor was rotated through 360 degrees in 5 degree

increments. The wiper voltage was indeed the required linear function of rotor angle. Next the total resistance was measured and found to be 6890 Ohm. Note that this was within the $6250 \pm 20\%$ (5000 - 7500) Ohm tolerance allowed for this potentiometer.

When notified of this anomaly the manufacturer said that it was typical for the total resistance of a conductive plastic pot to change after thermal cycling. The mechanism was explained as follows: conductive plastic is made of carbon particles in an insulating matrix, co-cured at 160°C (and rated for operation up to 125°C). Thermal cycles change the insulating matrix on a microscopic level, allowing better conductivity between the carbon particles. Macroscopically these changes appear as a drop in the total resistance. The manufacturer said that as the number of thermal cycles builds, the rate at which the resistance drops will decrease and the resistance will eventually stabilize. The scratches and drops of silver paint used to linearize the pot have an effect on the rate at which the resistance stabilizes. The manufacturer assured me that the resistance changes would be uniform throughout the length of the resistance element and that the pot's linearity would not be affected by changes in the total resistance.

The eight flight WSA pots went through additional thermal cycling as part of the steering actuator qualification test program. After those thermal cycles, the total resistances were found to have changed by +73 to -283 Ohms. Another data point comes from the MIL-PRF-39023-style pots: between manufacture and use, the total resistance of each one dropped from 200 to 400 Ohms.

From the beginning, WSA Potentiometer S/N 1039 was an outlier, with a total resistance 750 Ohms higher than its nearest neighbor. When S/N 1039 was 5 weeks old, it took advantage of a thermal cycle to drop its total resistance by 500 Ohms to a value more in line with, but still higher than, the rest of the batch. While this drift was significant, 1039 has always been within tolerance, and testing proves its linearity. Based on the preceding failure analysis, it was determined that there was no problem with the pot. However, just to be safe, pot S/N 1017 was labeled "Limited Use (Non-Flight Part)" and was not used for flight.

LESSON 21. Drifting values and excessive variation within a lot may indicate trouble, even if the individual pots are within spec. Compare the pots to each other as well as to the requirements.

Conclusions

As of this writing, the "Spirit" and "Opportunity" Mars Exploration Rovers have been operating on the Martian surface for over two years. In spite of the difficulties encountered during flight qualification of the MIL-PRF-39023-style pots, the HGAG pots and the WSA pots, all pots on the Rover continue to perform reliably under very harsh conditions. It is hoped that the lessons provided in this paper will help other potentiometer users enjoy similar successes.

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