Investigation of International Space Station Major Constituent Analyzer Anomalous ORU 02 Performance

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The Major Constituent Analyzer (MCA) is a mass spectrometer based system that measures the major atmospheric constituents on the International Space Station. In 2011, two MCA ORU 02 analyzer assemblies experienced premature on-orbit failures. These failures were determined to be the result of off-nominal ion source filament performance. Recent product improvements to ORU 02 designed to improve the lifetime of the ion pump also constrained the allowable tuning criteria for the ion source filaments. This presentation describes the filament failures as well as the corrective actions implemented to preclude such failures in the future.

Nomenclature

AR	Atmosphere Revitalization	LEM	Life Extending Mode
CH_4	methane	MCA	Major Constituent Analyzer
CO_2	carbon dioxide	N_2	nitrogen
ECV	electrometer correction value	O_2	oxygen
H_2	hydrogen	ORU	On-orbit Replaceable Unit
H_2O	water	S/N	serial number
ISS	International Space Station	VGA	Verification Gas Assembly

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I. Introduction

THE Major Constituent Analyzer (MCA) is a mass-spectrometer-based system designed to monitor nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2) and water vapor (H_2O) in the atmosphere of the International Space Station (ISS). It is an integral component of the Atmosphere Revitalization (AR) subsystem that is part of the Environmental Controls and Life Support (ECLS) system, and is a primary resource for ensuring that the (O_2) and (CO_2) levels in the ISS atmosphere are maintained at safe levels.

The MCA, shown in Figure 1, is comprised of seven On-orbit Replaceable Units (ORUs) that can be serviced or replaced individually in response to periodic maintenance requirements. The modular design is intended to optimize the service logistics on limited-life components without having to change out the entire MCA. Of these ORUs, ORU 08 (Verification Gas Assembly) and ORU 02 (Mass Spectrometer Analyzer) are the more commonly replaced components. ORU 02 is the technological core of the MCA and consists of a gas inlet, an ion source, a single-focusing magnetic sector mass spectrometer, six spatially arrayed ion detection electrometers, associated electronics, and a 4 L/sec ion pump. The primary life-limiting items in ORU 02 include the ion source filament (of which there are two) and the ion pump. Considerable attention has been paid to determining the factors limiting these components, and these have been described previously[1-5]. Steps were implemented under NASA Change Request (CR) 10773A to reduce the incoming gas flow and improve operation of the ion pump in an effort to increase ion pump life time. Likewise, the tuning parameters used to optimize filament operation and ion source performance during manufacture have also been examined with the intent of extending filament life.
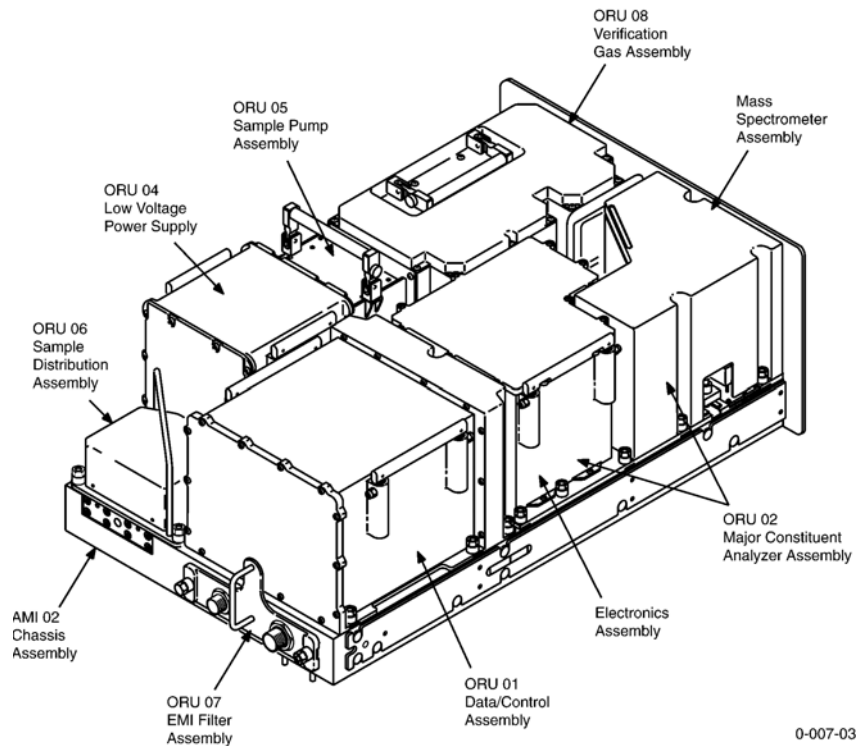
Figure 1: Major Constituent Analyzer

This paper reports on the investigation of premature on-orbit failures for ORU 02s F0001 and F0003 that occurred in 2010 and 2011. The failures of these ORUs involved the ion sources, and occurred in spite of the improvements described above. The results of the investigation reveal additional considerations that must be addressed to realize improved performance longevity. The on-orbit symptoms, investigation results, and corrective actions currently being implemented are discussed.

II.   On-orbit Anomalies

A. MCA ORU 02 F0003

ORU 02 F0003 was originally operated on orbit between 2002 and 2004. It operated for over a year before ion pump noise became a limiting issue and the MCA was operated in Life Extending Mode (LEM). ORU 02 F0003 was returned to ground and subsequently refurbished with a new ion source and ion pump. The ORU 02 was then relaunched, and re-installed on-orbit in the Lab MCA in Atmosphere Revitalization Rack 1 (AR1) in late 2009. The Lab MCA was not activated until ORU 01 F0001 with revised firmware Computer Software Configuration Item (CSCI) 4.24 was also launched and installed. The Lab MCA was activated on 9/13/2010. Upon activation, the ORU operated for approximately 24 hours with a steady filament current sensor reading of about 123 mA. After this, the filament current started to ramp up steadily, increasing to 141 mA in approximately 8 hours. The filament control circuit apparently reached an unstable feedback condition at that time and Filament 1 current railed at 195 mA. "Railed" is defined as the condition that occurs when the filament control circuit raises the filament current to the maximum level the power supply can provide and holds it there. **Error! Reference source not found.** shows the filament current during this time.
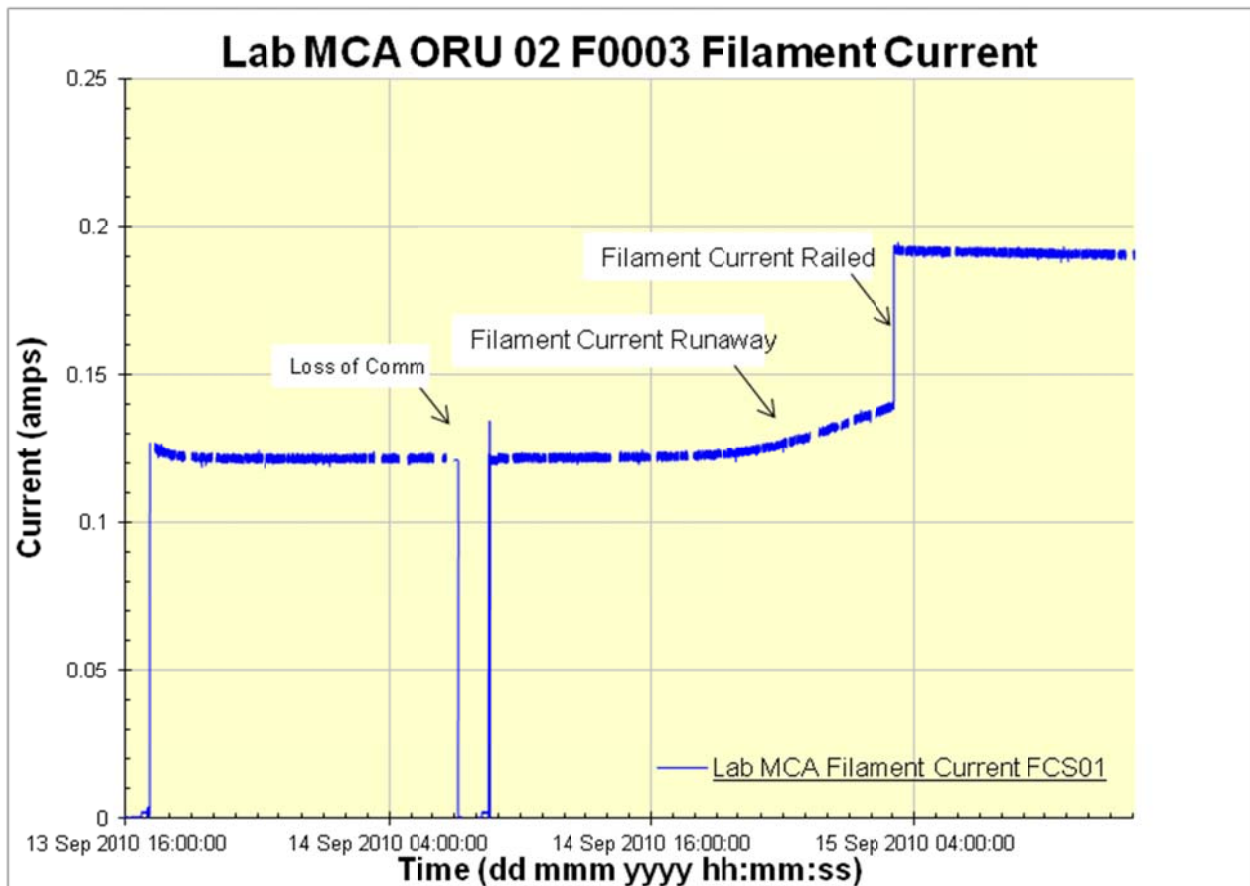
Figure 2: ORU 02 F0003 filament current over time, showing the rise that eventually railed at the maximum available current.

Subsequent to this initial Filament 1 failure, the unit was stopped and then restarted. At that time, Filament 1 passed Active Built-in Test (ABIT) during startup, but railed again a short time later. The ORU 02 was stopped and placed in Life Extending Mode (LEM). When it was restarted again on 9/21, Filament 1 did not pass ABIT and the unit completed startup on Filament 2. Subsequent to the failure of Filament 1, operation of ORU 02 Filament 2 was checked to determine whether the ORU 02 was likely to have any useful on-orbit life. It was decided to perform a one-week evaluation, and Filament 2 was activated on 9/30/2010. Upon completing the evaluation it was judged that Filament 2 would not likely have the infant mortality problems of Filament 1. Operation of the MCA with this ORU 02 was then discontinued due to problems with the CSCI 4.24 firmware, and ISS MCA operations switched to

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the Node 3 AR rack. Between the shutdown in September 2010 and the subsequent reactivation in May 2011, ORU 01 F0001 was swapped with ORU 01 Q0001 containing CSCI 4.18 to alleviate the identified firmware issues.

On May 13, 2011, ORU 02 F0003 was reactivated. The ORU operated for 24 days on Filament 2 before Filament 2 also failed. The symptom detected by the built-in test firmware was a lack of electrometer output, meaning that the electrometer sensor readings were zero. The symptoms indicated that the filament was consuming power while no ions were being generated, suggesting that something was interfering with electrons getting out of the electron gun. The MCA was operating using firmware CSCI 4.18 at the time of this failure. Firmware CSCI 4.18 has a filament current limit of 450 mA, so the Built-In Test (BIT) did not fail due to high filament current.

Following the failures described above, ORU 02 F0003 was removed from the Lab MCA and returned to ground on STS-135/ULF-7 for investigation. It was replaced with ORU 02 F0001, which was launched on STS-134/ULF-6.
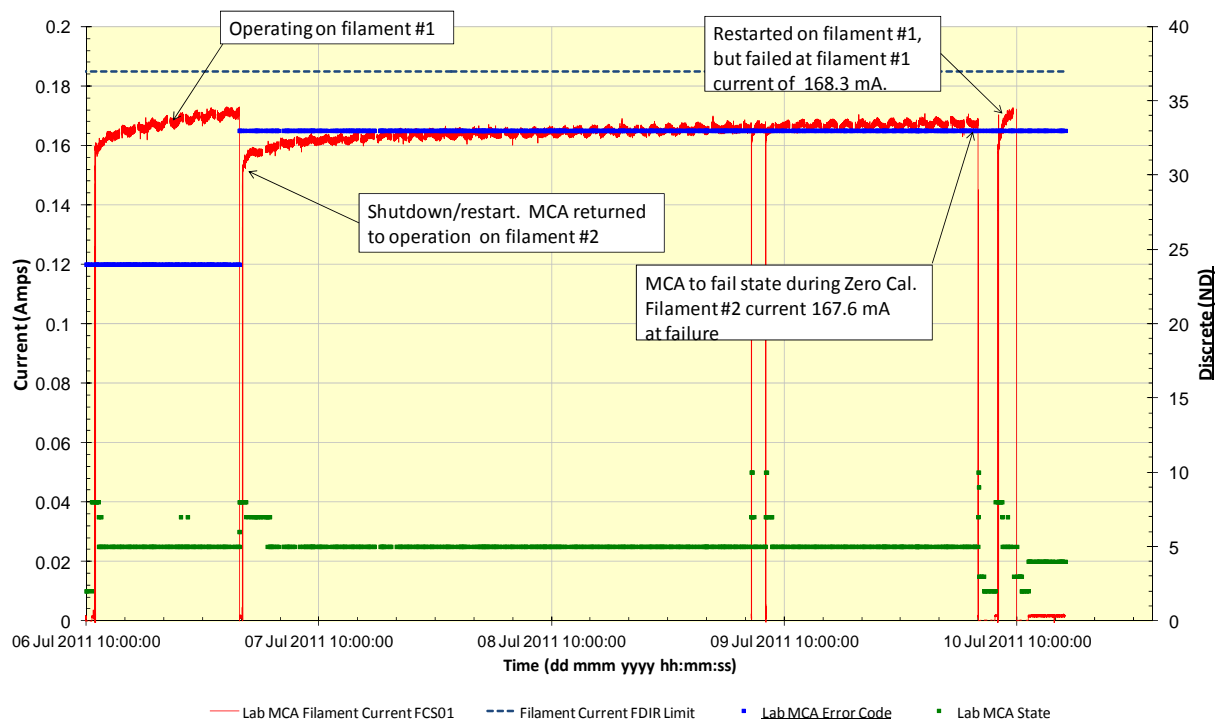
B. MCA ORU 02 F0001
ORU 02 F0001 is the first flight model ORU 02 and has had more flights and more run time on orbit than any other unit. The unit was initially powered-up in the ISS Lab module's MCA in early 2001, where it operated for over four months. During this first on-orbit operation, the ORU had a number of nuisance shutoffs of the filament, thought at the time to be due to a hardware ion pump current interlock. Upon return, the ORU 02 was modified to prevent ion pump spikes from shutting down the hardware, leaving protection of the filament up to the firmware. The ORU 02 was also updated with a low-flow sample inlet, intended to reduce the demand on the ion pump and provide a longer on-orbit life. Because of the short operating time accumulated on-orbit, remaining filament and ion pump life were considered sufficient for another mission; these limited life components were not changed prior to the second flight. Following the repair and update of ORU 02 F0001, the unit was returned to the ISS for operation and was installed in early 2006. Consistent with the expected life improvement afforded by the low flow sample inlet, the second on-orbit operation of this ORU 02 proved very successful, providing over 1000 days of operation. It was returned to ground and subsequently refurbished (including ion pump and ion source), marking only the second time an ion source had been replaced in a flight qualified ORU 02.

The Lab MCA was activated with the refurbished ORU 02 F0001 on 7/6/2011. The MCA operated on Filament 1 for 14+ hours. During this time, filament current rose steadily (but not linearly) from approx. 156 mA to 171 mA. The ORU then experienced a shutdown and restarted automatically. MCA came back up on Filament 2. Data indicate Filament 1 failed ABIT during restart. Filament high current FDIR limit was set by Range Limit Command (RLC) to 185 mA. Telemetry of Filament 1 current was 156 mA shortly after activation and 172 mA at shutdown, so the FDIR limit did not appear to have been reached. The FDIR limit of 185 mA was set in order to automatically protect the filament from a high current condition.

Filament 2 continued running, with gradually increasing current until 7/10 06:01. The ORU 02 then failed during a zero cal. During zero cal, the filament is briefly turned off and then is turned back on. It has been found that filament current overshoots its steady state value during turn on and then normally comes back down to the steady state value within about 30 seconds. It is suspected that since the steady state value was about 168 mA and the FDIR limit was 185 mA, the filament current went above the FDIR limit during this overshoot.

At 8:04, the MCA was restarted. Both filaments passed ABIT and the MCA reached Operate state on Filament 1. The MCA ran for almost an hour and then went to FAIL state at 9:38. The MCA was put into LEM for almost two days, until 2:01 on 7/12. In LEM, the ion pump is running, so mass spectrometer vacuum is maintained, but filaments are off. MOD performed a sensor static data dump requested at the 7/8/11 FIT. Results indicated MCA correctly received and stored the filament current FDIR limit of 185 mA. This confirmed correct commanding of the FDIR limit.

On July 12 at 2:01, the MCA was commanded to startup after a Functional Override Command (FOC) was sent that selected Filament 2. The MCA came up on Filament 2, indicating that Filament 2 passed ABIT. Over the next several days, the unit failed several times associated with Zero Cals. Consequently, it was decided to remove and return the ORU 02 to the ground for failure investigation. Additional filament activations were performed over the next three days to confirm the behavior of the two filaments and provide additional data in case reentry vibration or some other effect caused the behavior to change once the unit was on the ground.

Figure 3: ORU 02 F0001 filament current shown in blue.

III. Failure Investigation

Once ORU 02s F0001 and F0003 were returned to ground, a failure investigation team was formed to determine the root cause of the on-orbit failures. A full range of potential failure modes were considered, including on-orbit activities and conditions, general MCA operation, and failure modes specific to ORU 02s. The ORU 02s were visually inspected and then reactivated on a non-flight Integration and Test Unit (ITU) platform to replicate the symptoms observed on orbit where possible.

A. ORU 02 F0003

The two filament failures of ORU 02 F0003 were decidedly different – for Filament 1 a positive trend in filament current developed after a day of operation and, after rising steadily for 8 hours the filament current suddenly transitioned to the power supply's maximum output. Filament 2 showed no hint of instability over twentyfour days of operation prior to its transition to maximum power. Another nuance to the failures was that, while Filament 1 was at maximum power, the ion source continued to generate ions – nitrogen and oxygen signals were reduced but non-zero. When Filament 2 failed there were no ions produced in the source and all electrometer signals went to zero.

These signatures pointed to Filament 1 being driven over a period of hours to a point of operation where the control loop circuitry lost the capacity to generate sufficient electrons from the filament, and consequently drove the filament to maximum power. Eelctron Gun 2 simply stopped producing electrons altogether.

In a mass spectrometer ion source the function of the filament is to produce electrons through thermionic emission from a heated wire. The electrons produced are accelerated by electrostatic lenses in the electron gun section of the source and focused through a slit into the analyte ionization region. Within the ionization region, a small fraction of the electrons ionize gas molecules, producing the ions that the MCA's mass analyzer subsequently measures. The vast majority of the electrons exiting the gun do not interact with analyte and are collected at an anode across the ionization region from the electron gun.

How many electrons boil off a filament depends on the temperature of the filament, the filament's surface area, and the electric field near the filament's surface. Two equations describe thermionic emission under the conditions

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used in the MCA source: The Dushman[6] equation, Equation 1 below, is applied to heated cathode wires under standard vacuum conditions in the absence of space charge,

$$J_s = AT^2 exp^{\frac{-\varphi}{kT}} \approx 60\, T^2 exp^{\frac{-5200}{T}} \text{ amps/cm}^2 \qquad (1)$$

where J_s is emission per unit area, T is degrees Kelvin, and A, φ, and k are constants. At higher emission currents, the Space Charge Limit (SCL) condition can be approximated using the Mott-Gurney[7] law in Equation 2,

$$J = \frac{9\epsilon\mu V_a^2}{8L^3} \qquad (2)$$

where J is the emission per unit area, ϵ is the applied electric field, μ is the carrier mobility, V_a is the applied voltage, and L is the length of wire

Under the biases used in the MCA's electron guns, control of the filament temperature allows currents up to approximately 1 microamp per mil length of filament wire, assuming a 5 mil diameter tungsten wire, before space charge limitations kick in. The SCL effectively limits the electron guns to approximately 40 microamps maximum emission, and less as the filament wire diameter decreases with age.

The role of the filament control loop is to monitor the current output of the electron gun and apply more or less heat to the filament wire to maintain a constant emission. Typically the filaments operate with a center temperature of ~2000 K, and current through the wire is regulated to approximately 2 amps to maintain constant temperature. In the MCA, the control loop feedback is the anode current generated from the electron gun output. The gun design images all emission from the heated, middle length of filament through the aperture of the gun, for a gun transmission efficiency of 100%. If the filament physically bends away from its tuned position relative to the electrostatic lenses in the gun the transmission efficiency can go down. ORU 02 F0003 was configured to regulate gun emission well below the SCL constraint, but the control loop behavior was consistent with driving Filament 1 into saturation, implying that either the electron gun went out of focus or the SCL was driven to a lower value.

Upon disassembly of the source it was found that the SCL had dropped well below 40 µA for Electron Gun 1 by excessive oxidation of the filament. Electron gun inner surfaces were found coated with a black substance, confirmed by x-ray photoelectron spectroscopy and plasma etching to be a greater than 350 nm thick deposit of tungsten oxides. Figure 4 shows the filament block assembly, with the inner gold-passivated surfaces completely masked by the oxide deposit. Less obvious in the figure is that the filament wire has been etched such that the center of the wire is less than 3.7 mils in diameter.

The presence of oxides and lack of nitrogen in the deposit material suggest that either too much pure oxygen was admitted to the instrument during source tuning or the filament was heated before the analyzer's vacuum system was sufficiently dry. In vacuum tubes, small amounts of water vapor can lead to catalytic etching of tungsten filaments through something known as the water cycle[8]. The water signal was on-scale during that first day of operation on-orbit, implying that regardless of the source of oxygen, the etching had to be largely complete prior to installation on-orbit.

Figure 4: ORU 02 F0003 filament block assembly. Note that all surfaces with a direct view of the filament appear coated with a thick deposit of tungsten oxide, while those surfaces facing away from the filament or otherwise masked show the base gold color of the assembly.

Filament 1's failure left a significant deposit of tungsten oxide on the inner surfaces of Electron Gun 1. The deposit did not seriously affect operation of the gun's electrostatic lenses; tungsten oxide is sufficiently conductive to prevent charge buildup that might otherwise detune the gun. However this conductive debris, in a microgravity environment, could explain the sudden failure of the second electron gun.

Upon evaluation of the ion source, two of the gun 2 electrostatic lenses – the electron accelerator and a beam focus electrode – were found to have a soft short of approximately 1.3kΩ between them. The short was traced to the ion source itself but disappeared as the ion source was disassembled. No conductive foreign object debris (FOD), such as a metal sliver or whisker of tungsten trioxide, sufficiently large to span the gap between the lenses, was found. However, it is plausible, given the design of the ion source, for tungsten oxide to have deposited onto an insulating component of Electron Gun 2.

The effect of the short was to shift the voltage of the focus lens behind the filament to a significantly higher potential. The close position of the focus lens to the filament allowed this large potential to dominate the electric field, effectively redirecting the electron beam directly onto the focus lens rather than through the electron gun and into the ionization region of the source, dropping the efficiency of the gun to zero. The control loop responded by driving the filament current to the maximum output, but to no avail.

A. ORU 02 F0001

The failure symptoms of ORU 02 F0001 included characteristics that had not been previously observed, including apparent random restarts, occasional transitions to fail state, and the instrument switching between filaments on some restarts. These characteristics became important after the filament currents exceeded 160mA, suggesting that they were associated with filaments that were being driven into control loop saturation. That both filaments had positive current trends over time and one filament was eventually observed to go into runaway suggested that for both of these electron guns the underlying behavior was associated with control loop instability due to SCL.

The headroom to SCL was very thin for this analyzer due to a combination of factors that included: a very low-flow sample inlet frit; a small bias in the ion gun alignment that dropped the source efficiency about 30%, and lower-than average electron acceleration voltage. The first two terms increased the demand on the electron guns, forcing them to operate at 29 µA in order to ionize enough sample to generate the required ion currents at the detectors. The third term, dropping the electron acceleration voltage from a nominal 137 to 125V, yielded nearly a 20% drop in SCL, from about 40 µA to approximately 32 µA. As long as the electron guns remained perfectly tuned the roughly ten percent margin between the operating point and the SCL current was not important. However, the guns were poised to go into runaway if gun transmission efficiency dropped by more than 10% or the filament diameter dropped by more than 10%.

Both guns were observed to go unstable immediately after installation on orbit, suggesting that either transportation to orbit or the microgravity environment was adversely affecting gun efficiency by a few percent.

As the filaments neared runaway, nuances in ORU 02 F0001's operation led to the observed transitions to fail state and random restarts. When a filament runs into SCL, no amount of additional heat can provide the current being demanded by the control loop; the control electronics run the filament to maximum power in approximately 10 ms. A logic circuit in the filament control board automatically shuts off the filament power if it exceeds 250 mA. For this ORU 02, this circuit was tripping at the onset of runaway, causing the output of the ion source to go to zero. The firmware responds to a stopped ion source by initiating a restart if a filament shuts down during operation. If, however, the filament is disabled by the logic circuit during built-in test, the firmware marks the filament as dead and starts up the alternate filament. In both cases however, it was a transition to runaway exceeding the 250 mA threshold as the base behavior and the transitions too place too quickly to be observed in the 0.5 Hz MCA output telemetry data.

Finally, a number of factors affecting the resistance in the filament circuit, including the age of the filament, harness length, and contact resistances in the ion source, can limit the filament power supply output to less than 250 mA, allowing the filament control circuit to demand maximum power at just under the hardware protection trip threshold. ORU 02 F0001 was reprogrammed with a work-around that would send the MCA into fail state if the filament current was observed above 185 mA. This workaround was demonstrated to be involved in the observed transitions to fail state, again with the root cause being a filament transition to runaway.

IV. Conclusions

The on-orbit failures of two ORU 02s, associated with four filaments being driven to maximum power by their control hardware, had two separate proximate causes. In ORU 02 F0003 both failures were attributed to excessive oxidation of Filament 1, leading to an erosion of the SCL for that filament and the production of conductive FOD that shorted out the second electron gun. In ORU 02 F0001 the demand on the electron guns was high due to low sample flow and a lower-than-average ion source efficiency, while at the same time the SCL was depressed. Behind both issues is the use of low-flow sample inlet frits, implemented several years ago in order to improve MCA ion pump performance. The use of sample inlet restrictors at the low end of the design range effectively halved the pressure in the ion source, doubling the electron gun demand from 5–10 μA to today's 10 – 20 μA range. The erosion of operating margin to the design limit for filament control decreases the tolerances on ion source alignment and tuning voltages. There is also less tolerance for filament shifts associated with burn-in.

The corrective actions implemented as a result of the investigation include:
- Better control of air and water vapor control procedures during the various stages of manufacturing in which the filaments are operated, as well as during installation on orbit, to prevent filament oxidation.
- Operating the filaments for additional time prior to tuning the ion sources, minimizing the effect that stress-relaxation might shift filaments off-focus on orbit.
- Evaluating the electron gun performance as a function of demand to demonstrate that the SCL has not been degraded in optimizing other gun tuning voltages, with additional performance requirements implemented during final testing

It is expected that these additional steps will preclude the recurrence of the failures observed with ORU 02s F0003 and F0001.

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