Observations of Pt-Ne hollow cathode lamps similar to those used on the Cosmic Origins Spectrograph: photometry and vacuum testing.

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ABSTRACT

We report accelerated vacuum aging tests on two Pt-Ne lamps identical and/or similar to those installed on the Cosmic Origins Spectrograph (COS) to be installed in the Hubble Space Telescope (HST) in the fall of 2008. One additional lamp was aged in air at the National Institute of Standards and Technology (NIST). All lamps were tested at a 50% duty cycle (30 s on/off) at flight nominal (10 mA) constant current until failure. Calibrated spectra of all lamps were taken at NIST using the 10.7-m normal incidence vacuum spectrograph at various points in the life of the lamps. In this paper we report the results of the photometric, electrical, and thermal monitoring of the vacuum tested lamps, while the spectroscopic and air aging results are given in a companion paper (Nave *et al.*, 2008, SPIE 7011-134). We conclude that the lamps will satisfy the requirements of the HST/COS mission in terms of lifetime, cycles, and thermal and spectral stability.

Keywords: Cosmic Origins Spectrograph, vacuum ultraviolet, hollow cathode lamps, wavelength calibration, Hubble Space Telescope

1. INTRODUCTION

The Cosmic Origins Spectrograph[1] (COS),[†] to be installed on the Hubble Space Telescope (HST) in the next servicing mission (SM4), will perform high throughput, medium resolution (R=20 000) spectroscopy of point sources in the (1150 Å to 3200 Å) ultraviolet (UV) region. Wavelength calibration will be obtained by flashing the Pt-Ne hollow cathode lamps (HCLs) before, after, or during each science observation. These lamps will be used much more intensively than on previous space spectrographs. Previous experience of industry and the National Aeronautics and Space Administration (NASA) in space missions and thermal vacuum testing suggested that the intensity of the lamps might drop significantly over hundreds of hours of use,[2–4] leading to concern about their suitability for COS. In this paper, we discuss the results of air and vacuum Pt-Ne HCL lamp aging tests and their relevance to the COS mission. We limit our discussions here solely to the COS mission. For a more complete introduction to the history of the space applications of HCLs, please see Ref 5, a companion paper in these proceedings.

The original (1999) COS design reference mission[6] (DRM) requirement was:

> "**Lifetime:** The wavelength calibration subsystem shall be designed to provide the required data for the entire lifetime of the COS instrument. The COS shall be designed for a minimum of five years on-orbit operating life and a minimum of ten years calendar life. The pre-launch testing and calibration

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may represent the equivalent of one year of operations. The DRM estimates that COS may be prime instrument for up to 10,000 orbits, with as many as four wavelength calibration exposures per orbit. The DRM also estimates that approximately 500-1000 individual targets will be observed with COS over its lifetime. Each on-board target acquisition may require at least one exposure of the calibration lamp. The above estimates imply approximately 40,000 wavelength calibration exposures. If each exposure requires one lamp to be on for 3 minutes the requirement is for 120,000 min (2000 h) of use. These estimates imply approximately 40,000 turn-on cycles."

Initial estimates of COS HCL lamp degradation rates[4] indicated that lamp output was likely to drop 15% per A·h. While this was an acceptable degradation rate, during the initial COS thermal-vacuum testing in 2003 lamp output was measured to have dropped by as much as 5% in only 0.113 A·h (37% to 44% decline per A·h depending on whether a linear or exponential model is used). Other degradation estimates based upon actual experience with HST Goddard High Resolution Spectrograph (GHRS) Pt-Ne lamps in space showed drops of as much as 25% to 45% in just 50 h at 10 mA (0.5 A·h).[7] Air aging of similar lamps on the ground did not show such a radical degradation. The conclusion that the discrepancies between ground air-measured intensity changes and those on orbit, "arise from changes in the optical properties of either the lamp windows or the two MgF_2 surfaces feeding the light into the spectrograph"[7] does not eliminate the possibility of rapid HCL lamp degradation in vacuum or in space. This air/vacuum HCL aging project was designed to track the output of our flight spare and flight-like Pt-Ne lamps to get a more accurate determination of the degradation rate and to record any differences between air and vacuum testing. Pt-Ne lamps were chosen for COS instead of the longer lasting[2] Pt/Cr-Ne HCLs because the ultraviolet Pt line strengths are greater in Pt-Ne HCLs.[3,8]

It was discovered during thermal vacuum testing in 2003 that there are minor settling issues with the COS optical selection mechanisms that cause internal and external spectra to drift in the spectral direction. Without tracking and post processing correction, some science COS spectra would not meet specification. It was decided to flash the Pt-Ne HCLs during astronomical observations to simultaneously track this drift and provide wavelength calibration.[9] On both COS detectors the science and calibration spectra fall on different parts of detector, and both are true photon-counting detectors when operated in "TIME-TAG" mode (hence the name of "TAG-FLASH" for this COS mode). No previous HST instrument has operated its calibration lamps during science operations.

To minimize lamp usage, TAG-FLASH exposures are only long enough to provide enough counts for cross-correlation with a much higher signal-to-noise master Pt-Ne spectrum.* TAG-FLASHs are 5 s to 30 s in duration depending on observing mode (with an average of $\approx$ 20 s). COS science exposures will have a minimum of two TAG-FLASHs per exposure and a maximum of five for a single orbit exposure. The COS HCLs are also used during target acquisition, making the maximum number of TAG-FLASHs in the first orbit for each target 10, while the average is expected to be 5 to 7 per orbit.

Using the optimistic DRM estimate of 10 000 COS orbits and the upper estimates of the number of TAG-FLASHs per orbit we arrive at the following two on-orbit requirements (which supersede the DRM requirements):

1. The two COS HCLs combined need to handle 70 000 on/off cycles for the expected lifetime usage (closer to 100 000 is desirable).
2. At the average TAG-FLASH duration of 20 s, the lamps need to operate for only 400 h ($70\,000 \times 20$ s $\approx$ 400 h) at 10 mA (the nominal operating current), or 4 A·h. At the maximum TAG-FLASH exposure time (30 s) and maximum cycles (100 000) it is desirable that the two COS HCLs operate for a total of more than 850 h ($100\,000 \times 30$ s $\approx$ 850 h) at 10 mA (8.5 A·h).

These totals do not include use during ground testing ($\approx$ 240 h, 2.39 A·h, and 2850 cycles for both flight lamps combined) and orbital verification/calibration ($\leq$ 11 h, 0.11 A·h, and 1300 cycles). Combined these activities have used the COS flight HCLs for 251 h, 2.50 A·h, and 4150 cycles. Adding them to our requirements, we arrive

*Initially a ground-based master spectrum will be used. This will be replaced by a master spectrum created from all on-orbit TAG-FLASHs and some additional calibration exposures.

at our final COS + TAG-FLASH minimum requirements of 651 h, 6.50 A·h and 74 150 cycles, and maximum requirements of ≈ 1100 h, 11 A·h, and 105 000 cycles.

While not strict requirements, the following criteria are desirable in our calibration lamps

- Under normal usage, the lamps should not exceed COS thermal stability requirements.
- The spectra of the lamps should vary slowly and in a predictable way so that TAG-FLASH exposure times need to be modified only occasionally throughout the mission.
- Lamp intensity should not be strongly related to either the time since the most recent exposures or the length of those exposures. Lamp intensity should be within 10% on consecutive exposures.
- Lamp intensity should be stable during an exposure with variations not more than 50% greater than photon statistics.
- The lamps should turn on within 2 s of commanding.

In Sec. 2 we describe the experimental setup at the Applied Research Lab of the Center for Astrophysics and Space Astronomy (CASA-ARL) at the University of Colorado (CU), and in Sec. 3 we provide test results and discuss the implications for COS operations.

2. EXPERIMENTAL SETUP

2.1 Lamp Heritage

In 2004, a series of Pt-Ne HCLs were constructed at the Goddard Space Flight Center (GSFC) to provide calibration sources for HST and other NASA space missions. Two of these lamps were acquired for our tests. These lamps were constructed to be as similar as possible to the flight lamps for COS. The lamps have a Kovar flange which holds the MgF_2 exit window. Two COS flight spares (manufactured in 2000 by Imaging and Sensing Technologies of Horseheads, New York) were also acquired. The serial and lot numbers for these lamps are listed in Table 1. We do not have complete records of lamp usage prior to our acquisition of these lamps. As mentioned in Table 1, one lamp showed considerable use while the others appeared pristine. The three lamps used in testing showed no obvious use, but limited prior use (less than 0.14 A·h, or 10 h at 14 mA) is likely. Therefore, all of our lamp lifetime estimates are lower limits, and the actual age of the lamps for each spectrum are equally uncertain.

Lamp Name	Lot #	Serial Number	Comment
GSFC#2	040301-10	40424	Air tested at NIST; no obvious previous usage.
GSFC#3	040301-10	40418	Vacuum tested at CASA-ARL; no obvious previous usage.
Ball#1	WL-34046	03269-860	CASA-ARL setup/test lamp; obvious previous usage.
Ball#2	WL-34046	03450-860	Vacuum test at CASA-ARL; no obvious previous usage.

Table 1. Serial and lot numbers of the Pt-Ne HCLs used in our air and vacuum testing. Ball#1 lamp was used as an integration lamp and for some latency and repeatability tests. GSFC#2 was age tested in air at NIST, while GSFC#3 and Ball#2 were age tested in vacuum at CASA-ARL.

2.2 COS Lamp Housing and Electronics

The vacuum tested lamps were placed in flight housings as shown in the right panel of Fig. 2. The lamps are held in place by tori of vacuum compatible flexible epoxy (PR–1564 N Amber, PRC-Desoto Int. Inc.)[‡] as shown in the left panel of Fig. 2. In both panels, the front of the lamp is aimed towards the center of the page.

[‡]Certain commercial equipment is identified in this article to adequately specify the experimental procedure. Such identification does not imply endorsement by the National Institute of Standards and Technology, nor does it imply that this equipment is the best available for the purpose.

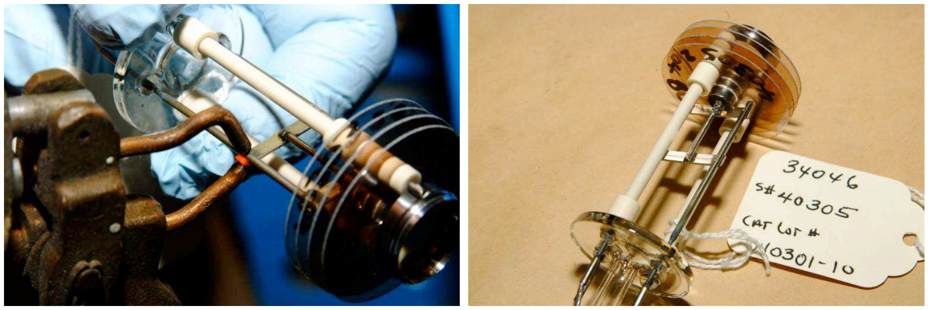

Figure 1. GSFC-type lamps (Lot #040301-10) in various stages of construction at GSFC.

Figure 2. The left panel shows the GSFC#3 lamp at 1008 hours. The tori of epoxy hold the lamp in the housing (right). The epoxy and the electrical connections are the only points of contact between the lamp and housing.

The lamps are controlled by a two-part custom controller (COS Calibration Lamp Test Set 568010 + 548010 UUT) loaned from Ball Aerospace that is functionally identical to the flight electronics. The controller is designed to run at constant current, and can drive the lamps at 3, 10, or 14 mA. The majority of testing was performed at 10 mA, while some end-of-life tests were performed at the other current settings, which are discussed in Sec. 3.5.

2.3 Optical Alignment

The vacuum lamp-aging tests were performed at CASA-ARL in a small ($\approx$ 1 m^3) vacuum chamber. The lamp housing was mounted to an optical bench $\approx$ 40 mm from a 15.2 mm diameter circular aperture (see the left panel of Fig. 3). While the lamp housing is fixed to the optical bench, the lamp itself has a $\approx$10 mm range of acceptable positions within the housing. A custom built 8-position linear stage positioned 12.7 mm diameter filters, a wire mesh (used as a neutral density filter), or a solid block behind the aperture (see the center and right panels

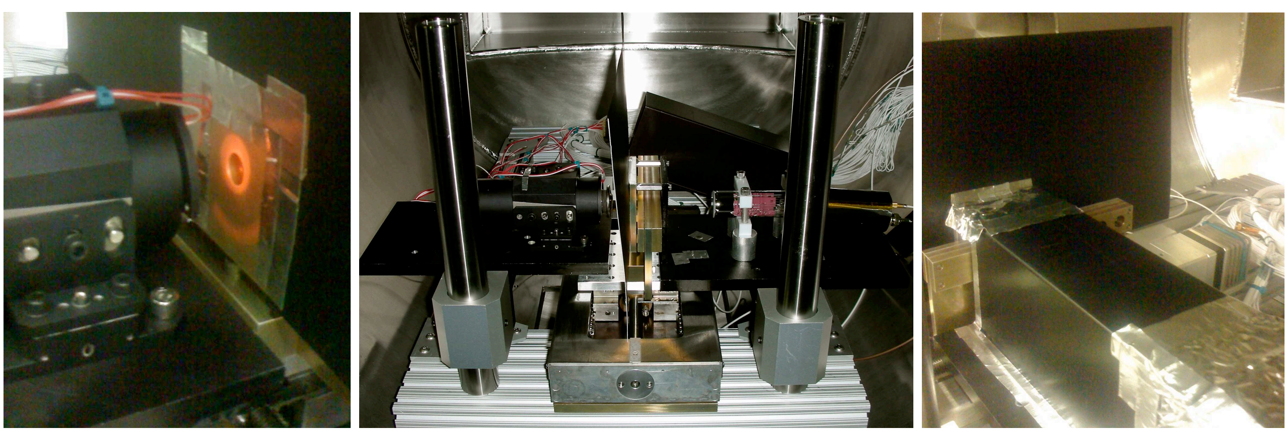

Figure 3. Vacuum lamp-test setup. Left panel shows an end-of-life lamp illuminating the fixed aperture block. Center panel shows a side view of the linear stage and the exposed PMT on the right. Right panel shows the test configuration of the PMT. Filter holes on the stage can been seen in the middle of the image just to the right of the PMT housing.

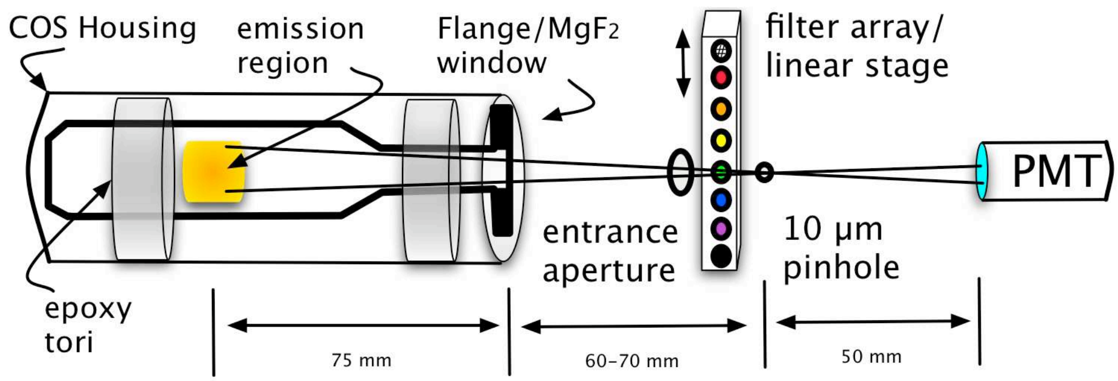

Figure 4. Block diagram of optical setup. The distance between the pinhole and the front of the lamp is variable due to installation uncertainties.

of Fig. 3). A block diagram of the optical alignment is given in Fig. 4. The linear stage was controlled by an electronic controller using custom controlling software. A 10 μm pinhole was mounted to backside of the linear stage, 60 mm to 70 mm from the lamp flange and approximately 135 mm to 145 mm from the HCL emission region. Fifty millimeters from the pinhole opposite the HCL is a 23 mm diameter CsTe photomultiplier tube (PMT) monitored by a photon counter with the appropriate amplifying and discriminating electronics. The PMT can be seen exposed in the center panel of Fig. 3 and covered in the right panel. Testing during alignment indicates that the UV beam fills the 12.7 mm diameter filter. For a 8 mm diameter HCL emission region, we would expect a ≈ 3 mm spot on the 23 mm diameter PMT.

Table 2 gives the COS wavebands and the Acton[‡] filters selected to approximate portions of these bandpasses. No filter was selected for the G230L mode as this is addressed by the other near ultraviolet (NUV) wavebands. As previously mentioned, in addition to the filters listed here, there are two additional stops on our linear stage: 1) a solid block to allow for dark count monitoring, and 2) a crossed-wire mesh to observe broadband lamp output at approximately the same lamp count rate as the brightest bandpasses. While there are no strict thermal requirements for the COS lamps, it is desirable that the thermal impact outside of the lamp housing be negligible. To test this, four remotely monitored thermocouples were placed on and around the lamp housing. These thermocouples were monitored by a relay box and custom controlling software. Temperatures

COS Grating/Channel	COS Waveband[a]	Vacuum Testing Filter[b]
G130M/FUV	1132-1469 Å	Acton 125-N
G160M/FUV	1382-1798 Å	Acton 145-N
G140L/FUV	1100-2378 Å	Acton 157-N-CF
G185M/NUV	1670-2127 Å	Acton 180-N
G225M/NUV	2070-2527 Å	Acton 220-B
G285M/NUV	2480-3229 Å	Acton 280-N
G230L/NUV	1334-2361 Å	No testing

[a]COS efficiency at wavelengths below 1150 Å will not be known until orbital verification.

[b]Certain commercial equipment is identified in this article to adequately specify the experimental procedure. Such identification does not imply endorsement by the National Institute of Standards and Technology, nor does it imply that this equipment is the best available for the purpose.

Table 2. List of COS wavebands and vacuum testing filters. All filters are 12.7 mm in diameter and are housed in commercial mounts. The bandpasses of the filters were selected to be fully contained within the COS bandpasses. No filter was selected for G230L testing.

were recorded every 61 s so as to sample all portions of the 30 s on/off lamp cycle. Thermocouples where placed 1) on the bottom of the lamp housing, 2) on the top of the lamp housing/top of the lamp (For Ball#2 a thermocouple was placed on the top of the housing, while for the first 500 h of the GSFC#3 testing the thermocouple was inside the lamp housing attached directly to the lamp above the cathode), 3) on the flange at the front of the lamp, and 4) in a distant corner of the vacuum chamber to track the ambient temperature. The thermocouple wires are visible in Figures 2 and 3.

2.4 Photometry Measurements

Two or more times a day, custom controlling software commanded a photometry test sequence. The test begins with a 150 s pause to allow the lamp to cool. Next the lamp is powered on for 120 s to allow the lamp to stabilize. The linear stage is moved through eight positions starting with a wire mesh then proceeding through the filters towards shorter wavelengths. At each filter, ten consecutive 1.5 s integrations are obtained. Finally, the lamp is turned off for 150 s to cool down, during which twenty dark readings of the PMT are taken. At the end of the test, the 30 s on/30 s off aging test is resumed. The lamp is constantly on for 280 s during the test. This time is accounted for in our aging results.

3. RESULTS

3.1 Photometry

As described in Sec. 2.4, periodic photometry measurements were performed at least twice daily by using filters matched to the COS wavebands. These results are displayed in Fig. 5 for the two vacuum-aged lamps, Ball#2 (on the left) and GSFC#3 (on the right). At the 500 h mark, each lamp was removed from its housing and delivered to NIST for spectral analysis. Upon return, the lamp was reinstalled in the housing and remounted onto the optical bench in the vacuum chamber. While the lamp housing is rigidly mounted to the optical bench, the flexible epoxy tori holding the lamps to the housing do not precisely reposition the lamp within the housing. As a result, the exact optical alignment is not repeatable and the photometric measurements were renormalized after each reinstallation. Normalizations as high as 20% were observed. This is within our expectations given the following three factors; 1) the lamp can be mounted closer or farther from the pinhole by as much as ≈10 mm (15% variability in flux due to inverse-square variations), 2) given that our pinhole camera image of the HCL emission region is much smaller than our detector (Sec. 2.3), we are using a different part of the PMT with each alignment (≈ 5% variations), and 3) errors in repositioning the linear stage filter stops to their optimum locations are possible (≈ 5% variations). These minor optical misalignments do not affect our photometric results or conclusions.

We observed an increase in intensity in all UV channels as the lamp aged. The lamps also became bluer as they aged, that is the far ultraviolet (FUV) channels increased in intensity more than the NUV channels. The increase in intensity seems to be directly related to the increase in voltage. Unlike the results obtained at the National Institute of Standards and Technology (NIST),[5] an increase in the size of the discharge region would have little effect on our observed fluxes. The focused slit arrangement at NIST would observe a decrease of flux with increasing discharge size for a constant or slowly increasing total flux. The COS optical path more closely resembles the NIST configuration, and we expect our on-orbit experience to be more like that reported by Ref. 5, than these photometric results, although the spectral redistributions observed in our photometry should be evident on orbit.

3.2 Thermal Environment and Stability

Figure 6 shows the temperatures recorded for the first 800 h of the GSFC#3 vacuum lamp test. In the upper panel we display the temperatures recorded on the top of the lamp, the bottom of the housing, the front of the lamp (the flange) and at a remote corner of the chamber. After 500 h, the thermocouple on the top of the lamp was moved to the top of the housing. The upward and downward temperature spikes on the top of the lamp are coincident with the periodic photometry tests as described in Sec. 3.1. The periodic drops to low temperatures mark intermittent shutdowns of our automated procedures. Note that after 500 h, the temperature measured on the flange is slightly higher. This is simply due to superior contact of the thermocouple and the flange after the 500 h spectrum was recorded at NIST.

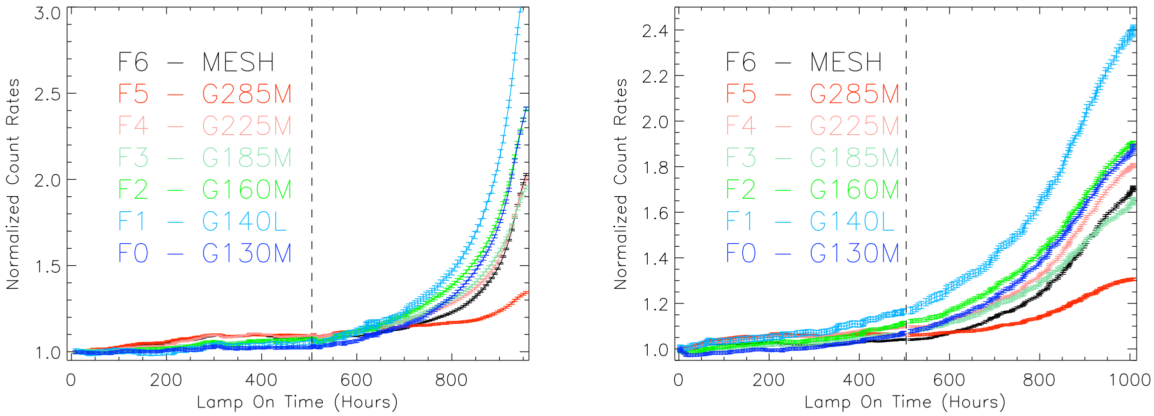

Figure 5. Photometry results for the Ball#2 (left) and GSFC#3 (right) lamps. The COS wavebands corresponding to the filters are given in the legend. The vertical dashed line at 500 h indicates the point in the lamp life where the lamps were sent to NIST for spectral testing. Count rates above 500 h are scaled to match those just prior to 500 h. Both lamps were observed to get brighter and bluer as the applied voltage increased.

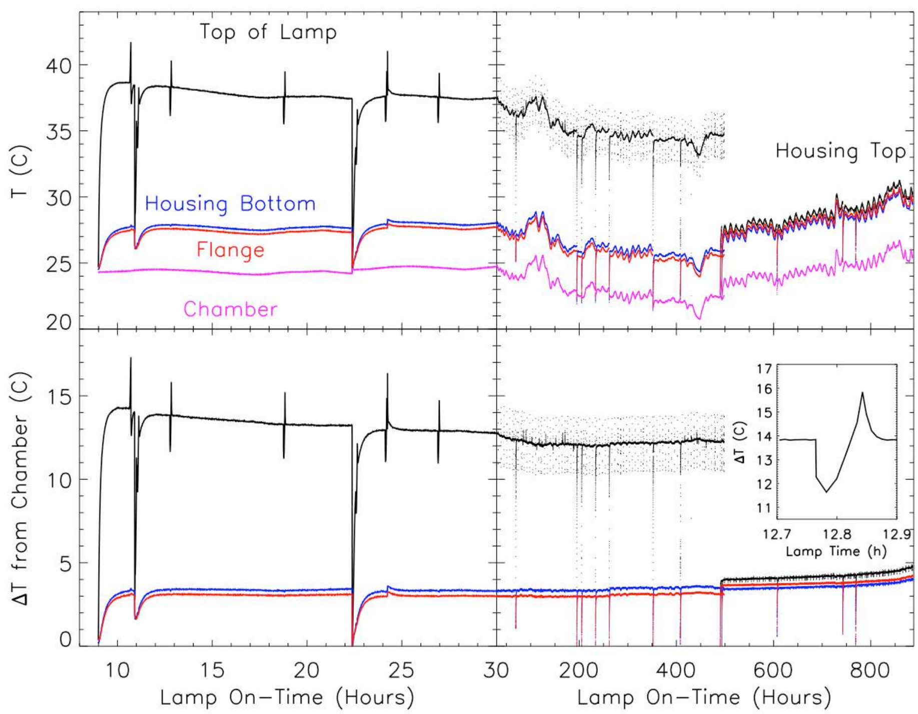

Figure 6. Temperature measurements of the GSFC#3 lamp testing. During the first 500 h, thermocouples were physically attached to the top of the lamp, bottom of the lamp housing, front lamp flange, and in a distant corner of the chamber. The temperature spikes are induced by our periodic photometry tests; temperature dropouts are due to infrequent system interruptions. Obvious diurnal and seasonal laboratory conditions are present. After 500 h, the thermocouple at the top of the lamp was moved to the top of the lamp housing. After subtracting the ambient chamber conditions, the thermal stability of the system becomes apparent (bottom panel). The insert in the bottom right panel shows the variations of the temperature on top of the lamp during one of our photometry tests.

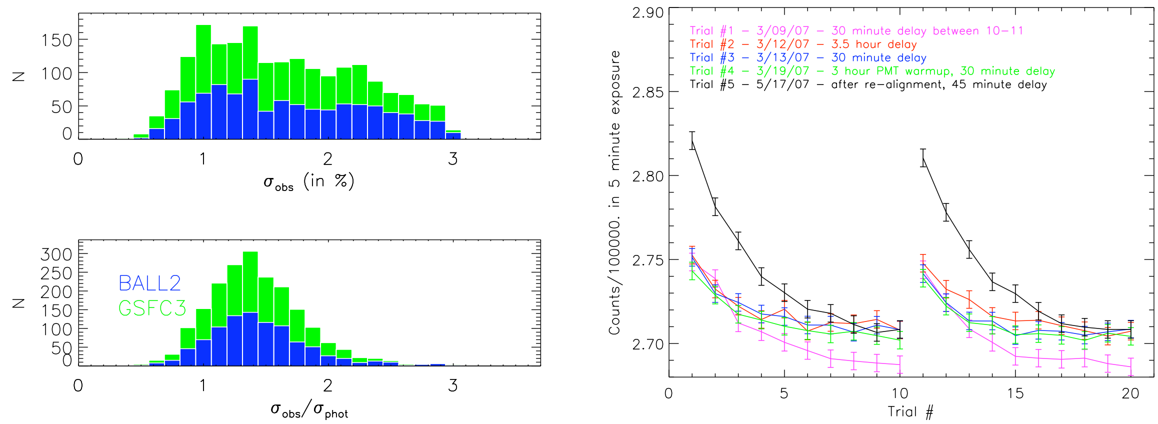

Figure 7. Intensity stability measurements of the two vacuum-tested lamps. Upper panel of the left figure shows the distribution of the measured 1-sigma standard deviations (σ_{obs}) for the individual photometry trials. Bottom panel shows the ratio of σ_{obs} to the expected Poisson standard deviations (σ_{phot}), indicating that the instantaneous lamp fluctuations measured for both vacuum tested lamps were small (a few % at most). Right figure explores whether recent lamp history has an impact on output. Five trials of two series of ten five-minute exposures with five-minute wait times between was performed using the 220-B (G285M) filter with the Ball#1 lamp. The wait times between the series for each lamp is given in the figure legend and varied from 30 min to 3.5 h. In Trial#5, the lamp was removed from the housing, then reinserted and realigned. These tests show that previous history is a minor factor in lamp output with the maximum fluctuation observed being $\approx 4\%$ under the extreme case of removal and realignment and $\leq 2.5\%$ under normal circumstances.

Diurnal, seasonal, and weekend related changes in the laboratory are reflected in the signature of all temperatures. In the lower panel of Fig. 6, we remove these external temperature variations by subtracting the ambient chamber temperature from the other readings. During the first 50 h of lamp usage we record a $\approx 2\,^{\circ}$C drop in the lamp temperature. After this the lamp is extremely thermally stable over its lifetime. The temperature measured at the bottom of the housing (the only lamp location with a consistent thermocouple location) varied less than $0.5\,^{\circ}$C once the ambient chamber variations were removed.

3.3 Photometric Stability

In addition to the NIST tests of spectral stability,[5] we performed two additional intensity stability tests. As previously described in Sec. 2.4, during each photometry measurement ten consecutive 2 s measurements were obtained on a lamp that had been running for two minutes. The statistical variations of the ten individual tests give us an estimate of the consistency of the lamp output combined with our measurement errors. The left panel of Fig. 7 shows the results of this test. Instantaneous lamp fluctuations vary only 40% more than predicted by photon statistics and were less than a few percent at the count rates observed in our photometry tests.

The right panel of Fig. 7 shows the results of a test designed to determine if the immediate previous history of lamp usage is a factor in lamp output. In this test five exposure sequences were performed with the Ball#1 lamp. The exposure sequences consisted of two sets of ten identical 300 s exposures performed at a 50% duty cycle (300 s on, 300 s off). A variable wait time occurred between the first and second set of ten observations. The lamp had been off for at least 12 h before each sequence to provide consistent initial conditions. As shown in the figure, the first turn-on was always the brightest with the lamp fading by 2% to 4% during the test. All cool-down times between the two series of tests (of which 30 min was the shortest) produced the same result of returning lamp intensity to its initial (brightest) count rate. Each of the 20 exposures in each test can also be used as a test for the delay in lamp ignition, as the lamp is turned on at the start of the exposure and the count rate is measured every 10 s during the exposure. Comparing the count rates of the first ten seconds to the median of the last 29 count rates, no latencies, or delays, of greater than 0.5 s were observed. This is consistent with lab testing of the flight lamps which showed no turn-on delay.

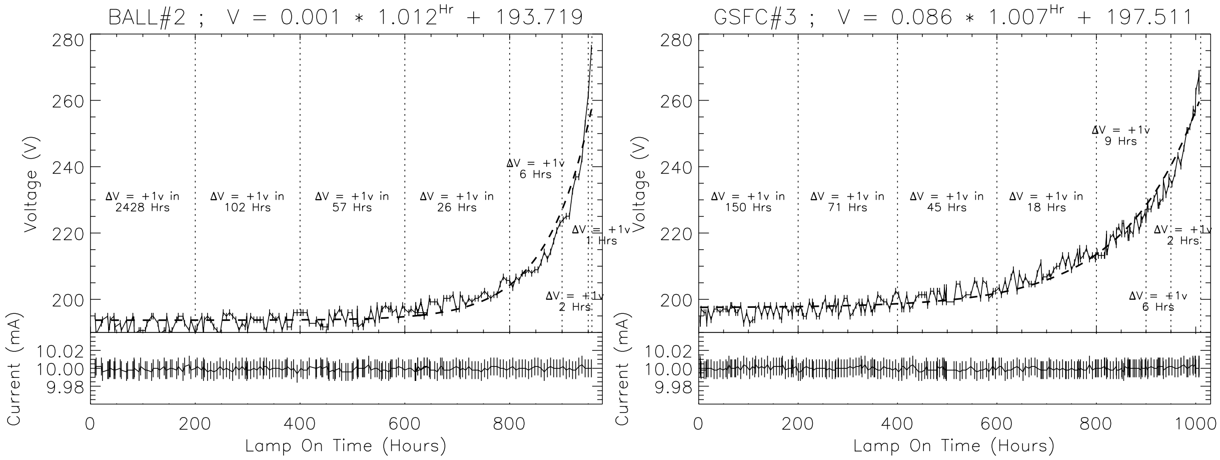

Figure 8. Voltage and current results for the Ball#2 (left) and GSFC#3 (right) lamps. Upper panels give the voltages reported from our constant current (10 mA) electronics. Bottom panels show the currents and our measurement uncertainties. Upper titles give the exponential fits to voltage versus time as shown by the dashed curves. Also indicated is the rate of voltage increase every 200 h up to 800 h, 800 h to 900 h, and every 50 h until the end of testing.

3.4 Voltage and Current Monitoring

During each photometry test, the average voltage and current measured over a 10 s period after a 30 s warmup period were recorded to an accuracy of 1 V and 0.1 mA. As described in Sec. 2.2, our electronics forced a constant current of 10 mA over the testing shown in Fig. 8. The left panel shows the results for Ball#2 and the right for GSFC#3. Exponential fits of voltage versus time (hours) are given in the figure titles. Also shown are the voltage increase rates in units of the number of hours to increase by one volt. These are given every 200 h up to 800 h, from 800 h to 900 h, and then every 50 h until the end testing. As previously pointed out in Ref 2, accelerating lamp voltage is an excellent indicator of lamp aging. Unfortunately, COS was not designed to report lamp voltage as part of the telemetry.

3.5 Longevity

Lamps were determined to be near end of life when the voltage required to drive the nominal (10 mA) current began to increase sharply ($\approx$ 1 V/h). Near end-of-life spectra of the GSFC#3 vacuum-aged and GSFC#2 air-aged lamps were obtained at NIST.[5] Specifics of the life and testing history for each lamp are given below:

- GSFC#2 (NIST air aging): As reported in Ref 5, this lamp provided 897 hours of useful emission. Spectra were taken at NIST at 0 h, 206 h, 500 h, 778 h, 783 h and 897 h. These calibrated spectra used approximately 26 hours of lamp life resulting in 871 hours of cycle testing ($871 \times 60 \approx 52\,300$ cycles). All testing on this lamp was performed at nominal (10 mA) current (8.97 A·h lifetime).
- GSFC#3 (CASA-ARL vacuum aging): This lamp provided 1050 hours of useful emission at 10 mA, and an additional 125 h at 14 mA. Spectra where taken at NIST at 0 h, 500 h, and 1000 h. Approximately 5.5 hours of usage was devoted to each spectrum, leaving $\approx$1159 hours of actual lamp testing. In vacuum testing, 315 photometry measurements were made, during each of which the lamp was run constantly for 280 s. The total cycling on this lamp exceeded 68 300 cycles. After 1000 h, at nominal current, the lamp output and voltage became erratic. At 1050 h, we attempted, without success, to run the lamp at one of the COS low current settings (3 mA), after which we ran the lamp at a one of the COS higher current settings (14 mA). For the first 60 of these hours, this lamp behaved similarly to the nominal current behavior (increasing voltage and output) until the lamp again became erratic.
- Ball#2 (CASA-ARL vacuum aging): This lamp provided 947 h of useful emission in our testing. Spectra where taken at NIST at 0 h and 500 h, and 203 photometry tests were performed. This lamp exceeded 55 400 cycles. This lamp was only tested at nominal (10 mA) current (9.47 A·h).

4. CONCLUSIONS

The mission requirement of the COS Pt-Ne HCL wavelength calibration lamps is five years of service and 10 000 orbits. During ground testing and calibration, the COS flight lamps have been used for ≈ 240 h, 2.39 A·h, and 2850 cycles. Orbital verification and calibration will require an additional 11h, 0.11 A·h, and 1300 cycles. Accounting for this usage, the two COS lamps together must meet the minimum requirements of 651 h, 6.50 A·h and 74 150 cycles; and our maximum-need requirements of ≈ 1100 h, 11 A·h, and 105 000 cycles (Sec. 1).

We have examined these Pt-Ne HCLs in air- and vacuum-aging experiments investigating their behavior in terms of :

- **Thermal Stability**: The COS Pt-Ne HCLs meet the thermal stability requirements of HST/COS. At nominal current and a higher usage than on orbit, the temperature excursions and gradients measured on the lamp housing would not violate COS thermal requirements.
- **Cycles**: Our test lamps lasted a minimum of 52 300 on/off cycles each, exceeding the two-lamp minimum requirement of 74 150 cycles. On average, our vacuum tested lamps lasted 60 000 cycles, exceeding the two-lamp maximum-need estimate of 105 000. At a maximum usage of 10 cycles per orbit and 1000 orbits per year, each lamp should last for 5 to 6 years of operation. At the expected usage of 7 cycles per orbit, and 800 orbits per year, these lamps should last at least 9 to 11 years each.
- **Functional Longevity**: Of our three test lamps, the air-tested lamp had the shortest life at 8.97 A·h. Each lamp should last for a sufficient number of Ampere hours to provide ≈8 years of service at maximum usage (300 s/orbit ×1000 orbits/year @ 10 mA), and 19 years at predicted COS usage (150 s/orbit×800 orbits/year @ 10 mA). These values include the estimated 2.5 A·h used during ground testing of the COS flight lamps. The two-lamp minimum requirement of 6.5 A·h is easily met with one lamp, and the maximum-need estimate of 10 A·h is easily met with two lamps.
- **Spectral Stability**: The NIST spectrally-resolved radiometric studies[5] show spectral stability well within the operational needs of COS (a 4% drop per A·h over the first 500 h). Long term instantaneous and previous-history tests show that lamps are repeatable to a few percent on short time scales. On-orbit, we expect the lamps to perform long-term as indicated by the NIST flux measurements[5] (slight drop in intensity with time) rather than our results (dramatic increase in step with the increased voltage), as the NIST optics more closely resembles those of COS.
- **Latency**: No turn-on delays of longer than 0.5 s were observed.

These results are consistent with previous HCL experience on HST with the Faint Object Spectrograph, GHRS, and the Space Telescope Imaging Spectrograph, although usage on these instruments was much lower. Other factors such as the loss of convective cooling inside the lamps on orbit (micro-gravity) and differing radiation environments are still considered to be unknown factors affecting HCL lifetimes. However, it appears that we have comfortable safety margins for the minimum expected COS mission duration of 5 years and could likely support a 10 year mission.

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