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Space- and ground-based non-accelerated long lifetime data for ruggedized commercial Non-Planar Ring Oscillator (NPRO) lasers

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ABSTRACT

Lifetime data is presented for ruggedized commercial NPRO lasers used in the Tropospheric Emission Spectrometer (TES) Instrument on NASA's *Aura* Earth-orbiting spacecraft, including 20 years of data from two life test units on the ground, 12 years of on-orbit data from TES Laser A, and 2 years of on-orbit data from TES Laser B. The TES lasers are diode-pumped Non-Planar Ring Oscillator (NPRO) lasers using Nd:YAG crystals. Since accelerated life testing was not possible on the complete laser, early prototype lasers that had gone through thermal cycling and vibration testing were placed on non-accelerated life tests with the hope of gathering at least a couple of years of data before launch. Long-term lifetime data for hybrid laser systems in space applications is not abundant, and out of necessity, accelerated reliability testing is usually done over a relatively short time with a large number of devices. The data presented in this paper is unique as it tracks the optical power output over time of a total of four lasers on the order of decades rather than months or years. Two of the lasers have each been on life test for over 20 years on the ground and are still operating, and the other two lasers have been on-orbit for 14 years. TES Laser A was still operating when the TES Instrument was decommissioned in January 2018. Therefore, the data presented covers over 450,000 non-accelerated device-hours, with 23% of those hours being in space.

Keywords: laser, lifetime, space

1. INTRODUCTION

1.1 TES Instrument on Aura

NASA's Jet Propulsion Laboratory (JPL) developed the Tropospheric Emission Spectrometer (TES) which launched on the Aura spacecraft on July 15, 2004. Aura is a member of the series of satellites that make up the Earth Observing System (EOS) that has a polar orbit around the Earth. TES was designed to survive this orbit including the thermal, dynamic and radiation environments of launch and orbital operations. TES is a Fourier transform spectrometer that uses a narrow linewidth laser to trigger sampling of the interferogram. The laser selected for use on TES is a laser diode pumped Nd:YAG NPRO laser built by Lightwave Electronics Corporation (LWE).

1.2 Description of the lasers on TES

The lasers flown on TES are ruggedized versions of the commercial Model 125 diode-pumped, solid-state, Non-Planar Ring Oscillator (NPRO) laser manufactured by Lightwave Electronics Corporation (LWE). The NPRO crystal, made of Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG), is end-pumped by a C-mount, AlGaAs 808nm semiconductor diode laser that is focused into the NPRO crystal by, first, a cylindrical lens and then by a Graded Index (GRIN) lens. A magnetic field is applied to the NPRO to utilize the Verdet effect of the Nd:YAG and force the ring resonator to lase only in one direction.[1] Back facet leakage from the laser diode is monitored with a silicon photodiode chip (the diode monitor, or DMON, as it is referred to in Figure 1). The 1064nm output of the NPRO is directed (via turning mirrors) through a quarter-wave plate, optical isolator, and half-wave plate and then focused into a single-mode optical fiber using a GRIN lens. A beamsplitter transmits 1% of the 1064nm laser light to an internal photodetector (the internal laser monitor, LMON) just before the beam is coupled into the output fiber. The optical laser power from the output fiber pigtail is referred to as the fiber monitor, or FMON. See Figure 1 for the optical layout of the Model 125, circa 1998.

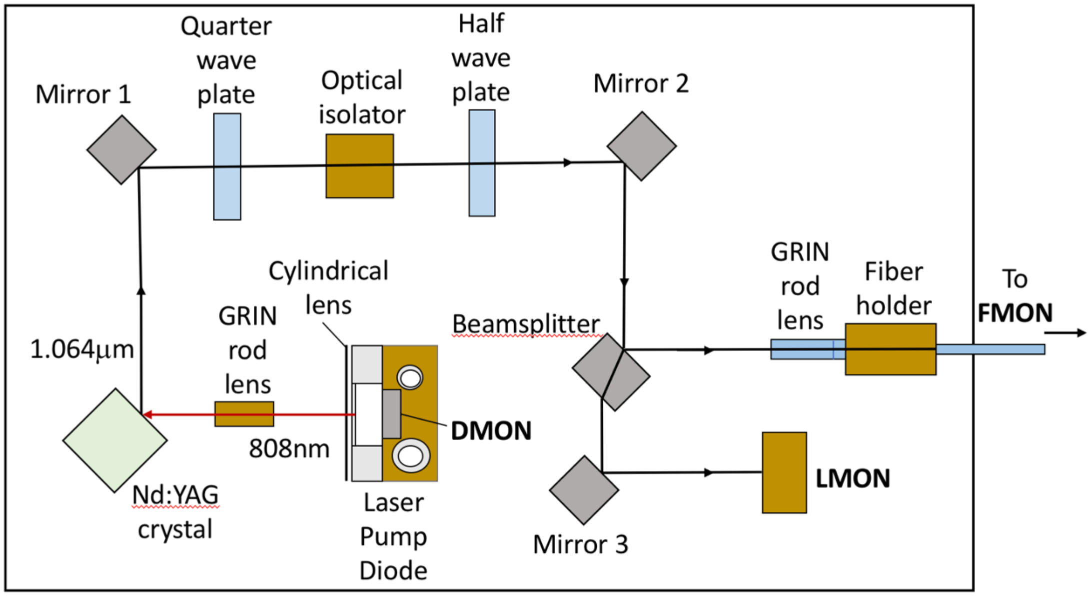

Figure 1. The optical layout of a Model 125 Laser from Lightwave Electronics Corporation, circa 1998.

1.3 Initial commercial laser environmental testing

After selection for TES, LWE delivered two Brassboard (BB1 and BB2) Model 125 lasers to JPL. The lasers were taken through vibration and thermal environments representative of those expected on the TES Mission in order to evaluate their performance. LWE conducted environmental tests on BB1 before delivering to JPL, and JPL conducted the environmental tests on BB2 at JPL. The only mechanical changes that were made to BB1 and BB2 in comparison to the commercial lasers was to epoxy the magnets in place rather than relying on the strength of friction and magnetic attraction to keep them in position and to use a higher temperature solder to secure the fiber holder in place.

BB1 experienced a 39% drop in output power (FMON) following vibration tests. That drop in power was then compensated for by increasing the diode current such that the laser output was 13.8 mW. BB1 was then thermally cycled from -20°C to +50°C over ten cycles and no further output power degradation was observed. BB2 started with an output power of 30mW. No output power drop was observed following vibration tests, powered temperature cycles, and the 48-hr unpowered hot soak at +50°C. However, FMON dropped 40% and LMON dropped 30% following ten unpowered temperature cycles from -20°C to +50°C. Unlike BB1, the BB2 current was not adjusted to compensate for the power loss during the environmental tests. The diode power measured by the DMON detector did not decrease as a result of the environmental tests on either Brassboard laser, indicating that there was no damage to the pump laser diode. The greater optical misalignment sensitivity of FMON versus LMON is expected, as coupling into the output fiber is more difficult than beam alignment to the internal LMON photodetector. The two Brassboard lasers were placed on non-accelerated life testing after the environmental testing was complete.[2]

1.4 Reliability concerns and mitigations

Lack of alignment stability in the laser under vibration and temperature cycling was the main lesson learned from the initial environmental testing, so JPL evaluated the design of the commercial NPRO lasers and suggested additional feasible design changes (not requiring a complete re-design) to adapt them for surviving launch and thermal stresses. The optical alignment of the NPRO laser cavity itself is inherently stable due to its monolithic design, but the alignment stability of the pump diode to the NPRO and of the NPRO output beam to the output fiber pigtail was a concern. The suggested changes included redesigning the laser diode mechanical mount with a second screw to more securely hold it in place, changing the material of the heatspreader (underneath the diode mount) from Aluminum to

Copper (same as diode mount material), removing the indium foil from beneath the diode mount, and changing the attachment method for the NPRO crystal on its carrier to a high T_g (glass transition temperature) epoxy.

In addition to the effort to redesign the NPRO lasers to survive the TES environments, the laser system and its components were evaluated for their abilities to meet the mission lifetime requirement of 5 years. From experience with prior space missions and industry understanding of and testing of their devices, two components were highlighted as potential lifetime concerns: the thermal electric coolers (TECs) and the pump laser diodes. As the NPRO laser designer and manufacturer, LWE had field test data on their NPRO lasers showing that the top three sources of field failures, in order, were fiber misalignment, diode failures, and TEC failures.

In order to address TEC concerns, both TEC types (the large one that maintains the pump diode temperature and optical bench temperature and the smaller one that controls the Nd:YAG crystal temperature) were screened before being considered acceptable for use in NPRO lasers for TES. The screening consisted of careful visual inspections looking for any signs of cracks or inadequate solder and AC resistance tests to ensure that the TECs were not damaged in a way undetectable by visual inspection.

After reviewing the laser diode manufacturer’s lifetime data on the lasers intended for flight, it was decided to fly a redundant laser and to design each NPRO laser to a 2.5 year lifetime so that the two lasers together could support the 5 year planned mission life. Thus the laser subsystem was designed with two NPRO lasers, the output of each going to an input port of a 2x2 single mode fiber coupler. One output port of the coupler connected to a single mode optical fiber that launched the laser light into the TES interferometer. The second output port of the coupler connected to a single mode optical fiber that brought the laser light to an InGaAs photodetector which provided the in-flight measurement of FMON.

Diode failure is a primary reliability concern for all diode-pumped lasers. To increase the likelihood of the pump laser diodes surviving for the required 2.5 years, the diodes were purchased from a single up-screened commercial wafer from LWE’s diode manufacturer, Spectra Diode Labs (SDL). Four diodes from this “champion” wafer, for which no failures were allowed during its 500 hour wafer qualification test, were given an additional 1,600 hour surveillance test to further verify the quality of the wafer. The flight diodes all came from the same assembly run which was performed in SDL’s space-qual laser diode production area. Die bonder and wire bonder equipment was qualified with destructive tests before the assembly run. 100% wire bond pulls were performed on the flight lot and 100% visual inspection was performed per space-qual criteria by a space-qual QA inspector.

It was also decided to run the diodes greatly de-rated. LWE’s experience with the SDL pump diodes indicated that the diode failure rate was related to the ratio of operating current to maximum current (Imax), with no diode failures occurring below about 42% of Imax. Thus the TES flight lasers were set to operate close to that current level.

As an additional part of the laser diode up-screening, SDL performed accelerated life testing on lasers from the flight wafer. Seventeen laser diodes that came from the same qualified wafer and assembly run as the flight diodes and that passed all screening tests were put on accelerated life test for 8,550 hours at an ambient temperature of 50°C and a constant current of 1.27A, corresponding to an emitted power of 0.9W. See Figure 2 for a plot of the accelerated life test results. One out of the 17 diodes failed within the first 2,000 hours, and four more diodes failed between 2,000 and 3,000 hours, all having adjacent serial numbers to the first failed diode. All five of the failed diodes had a threshold current that was ~20% higher than the other 12 diodes on life test, indicating the likelihood that the five failed diodes are all from the same area of the wafer. Flight diodes were selected such that none came from the “bad” part of the wafer, so the SDL lifetime prediction calculations do not include the five early failures. However, as is obvious from Figure 2, eight additional failures occurred during the remainder of the year-long life test, and a ninth laser was starting to degrade and was headed to failure, which was an unexpectedly high number of failures during the life test.

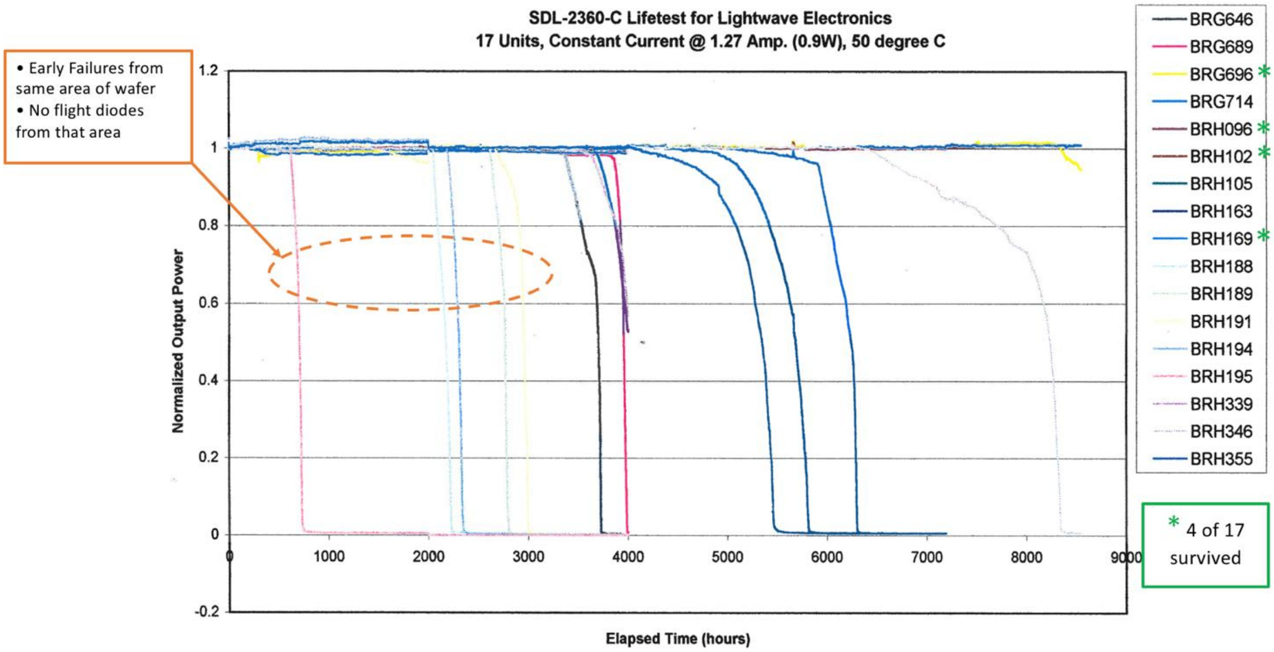

Figure 2. Annotated plot of TES laser diode accelerated life test data provided by SDL.[3]

From a failure analysis limited to electro-optical tests and visual inspection, SDL hypothesized that the failures were dominated by a wear-out mechanism. SDL lifetime predictions based on that assumption yielded a projected median life for the flight diodes ranging from 9 to 69 years (using acceleration factors to account for the lower flight temperature and operating current). The range comes from the best and worst case assumptions for the failure activation energy, Ea (0.8eV and 0.5eV), and power acceleration factor, n (2 and 1). Since SDL was not able to definitively determine whether the failure mode was sudden/random failure or wear-out failure, they also calculated the projected life using the acceleration factors for sudden/random failures. This yielded a projected life of 113 years when using a 60% Confidence Level.[3]

JPL conducted an independent calculation of the projected lifetime from the SDL accelerated life test data. Using the following industry standard Arrhenius equation[4,5] to calculate the acceleration factor ($A_f(T)$) associated with the case temperature difference between the test and use conditions:

$$t_{use}/t_{stress} = A_f(T) = e^{\{(Ea/k)*(1/Tuse-1/Tstress)\}} \qquad (1)$$

Where:
t_{use} = lifetime at the use temperature
t_{stress} = lifetime at the stress temperature
$A_f(T)$ = Acceleration factor for case temperature
Ea = Thermal Activation Energy
k = Boltzmann's Constant = 8.62×10^{-5} eV/K
Tuse = Use Temperature in Kelvin
Tstress = Stress Temperature in Kelvin

Then given Ea = 0.4eV, Tuse = 298.16°K (or 25°C), Tstress = 323.16°C (or 50°C):

$$\underline{A_f(T) \quad = 3.33}$$

Next, using the following industry standard inverse power law equation[4,5] to calculate the acceleration factor ($A_f(P)$) associated with the operating output optical power versus the stress condition output optical power:

$$t_{use}/t_{stress} = A_f(P) = (P_{stress}/P_{use})^n \tag{2}$$

Where:
$A_f(P)$ = Acceleration factor for output optical power
P_{use} = Output optical power during operation
P_{stress} = Output optical power during stress test
n = Empirically determined power acceleration parameter

Then given $P_{use} = 300$mW, $P_{stress} = 900$mW, and $n = 2$:

$$\underline{A_f(P) \quad = 9}$$

Then, to calculate the Failures-In-Test (FIT) rate, λ_{hour}, use the following electronics industry standard equation:

$$\lambda_{hour} = X^2(\alpha,\nu)/2DHA_f \tag{3}$$

Where:
$X^2(\alpha,\nu)/2$ = Chi-Squared: probability estimation for the number of failures
α = Confidence Level (CL)
ν = Degrees Of Freedom = 2r + 2 (for reliability calculations)
r = Number of failures
D = Number of devices tested
H = Number of test hours per device
A_f = $A_f(T)$ x $A_f(P)$

And to calculate the estimated Mean Time To Failure (MTTF) in years, use the following equation:

$$\text{MTTF} = 1/(\lambda_{hour} \times 24 \times 365) \tag{4}$$

So, given $\alpha = 90\%$, $\nu = 18$, $r = 8$, $D = 12$, $H = 8{,}550$, $A_f = 30$:

$$\underline{\text{MTTF} \quad \sim 27 \text{ years}}$$

Therefore, despite observing more failures than expected during the laser diode accelerated life test, the conservative MTTF calculation indicates that the laser diode lifetime should support the TES mission life of 5 years, especially when utilizing a redundant laser and running the laser diodes significantly de-rated.

1.5 Flight laser development

Even though the accelerated life test predicted that the laser diodes would be reliable enough for the 5-year mission, the results of the environmental testing on the Brassboard units showed that more work on the alignment stability was necessary before moving on to build the Engineering Model (EM) laser. Therefore, before starting work on the EM, three Pre-Engineering Model (Pre-EM) lasers were built to validate the design improvements intended to make the Model 125 lasers more rugged. The Pre-EMs incorporated JPL's suggestions aimed at improving alignment stability: new copper heatspreader, two-screw diode mount, new optical bench to accommodate the larger diode mount, and using a high T_g epoxy to mount the NPRO onto its carrier. In addition, a singlemode fiber pigtail replaced the polarization-maintaining fiber pigtail that the commercial lasers used, and the development units were purged with dry air instead of dry nitrogen at SDL's suggestion (to improve the reliability of the laser diode).

The Pre-EMs were still exhibiting excessive power loss starting at around the 1,200-hour mark on the life tests, so while the EM unit was built in the same way as Pre-EMs 2 and 3, a pre-conditioning/pre-shrinking step on the fiber pigtail jacketing was added. This pre-conditioning step was intended to reduce compression forces on the fiber due to jacketing shrinkage, thereby reducing force on the fiber alignment assembly that could cause misalignment over time. Right after the EM unit was built, LWE moved to a new location, so two additional units were built to verify the process in the new facility. These units were named “Post-EM” 1 and 2.

During the course of building the Post-EM units, life test data continued to be gathered on the units built so far, and the power trends suggested that there were additional misalignment mechanisms that needed to be addressed before building the flight lasers. Several possible sources of misalignment were identified and studied and then a few of the most practical design changes were approved by the TES project and incorporated into reworked versions of the Post-EM units that were called PoEM 1B and PoEM 2B. All of the changes were limited to the fiber block assembly that governs the alignment between the output laser beam of the NPRO and the fiber pigtail output of the laser. The changes that were made include: fiber blocks with tighter tolerances, more stable adhesives, and removal of a reinforcing ring that was causing a mechanically over-constrained assembly.

Results from the life tests of the PoEM 1B and 2B lasers prompted additional process changes to the flight laser build design. Rather than build additional engineering model lasers, the decision was made to go ahead and incorporate changes into the flight laser builds that were deemed to pose little risk. To mitigate the risk of the untried changes, the decision was made to build 10 candidate flight lasers and then select two out of the 10 as the lasers that would fly. The flight model lasers were called ProtoFlight (PF) units, and were designated PF1 through PF10 in build order.[6]

Some concern remained about alignment stability going into the flight model builds, so a life test was designed to monitor the PF lasers over non-accelerated operation for more than 1,200 hours (when the Pre-EM lasers had started to decline), and yet not use up too much of the laser life. The length of the life test was set at ~10% of the required laser life, or 2,160 hours. An accelerated life test was not possible because there was no physics-based model with which to accelerate the life tests. All 10 of the lasers performed well in the life test with only PF1 exhibiting close to the 20% decrease that would have denoted a failure, with a drop in power of 16% after the life test. Since PF1 was the first unit where the additional untried process changes were started, more rework was performed on that laser than the others, and that could possibly explain the instability. The two lasers that were selected for flight were PF2 (Laser A), and PF8 (Laser B). See Figure 3 for the life test data from the 10 flight candidate lasers along with the Pre-EMs, EM, and Post-EMs.

To further reduce risk, a 10x gain switch capability was added to the interferometer laser detector. A more accurate calculation of the minimum laser power needed to collect science data was performed yielding a required value of 10μW. The lasers start out with ~40mW output, but the light launched into the interferometer is quickly halved by the 50/50 fiber coupler necessary to maintain a redundant laser, resulting in ~20mW into the interferometer pre-launch. Still, with only 10μW needed for science collection, the lasers could degrade by 1,000x and the instrument would still work. Even though the early Pre-EMs declined rapidly after 1,200 hours, Figure 4 shows that even the Pre-EMs eventually stabilize to at least ~5mW, so there was confidence that the lifetime requirement would be met.

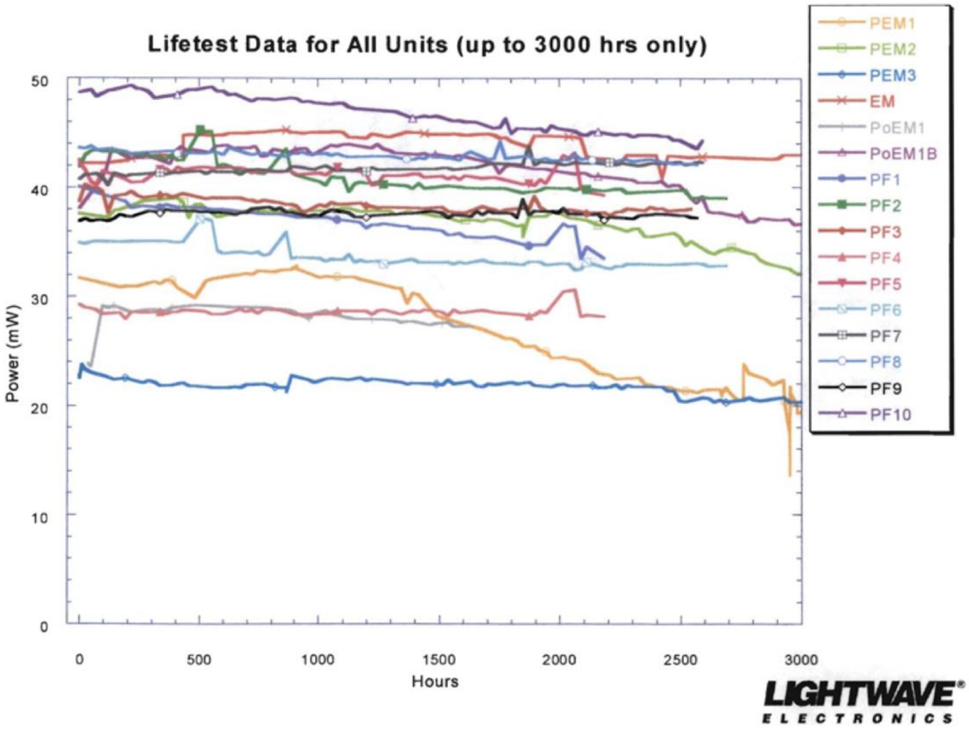

Figure 3. Lifetime Data from all lasers built in the TES Flight Laser effort (up to 3,000 hours only, for better view of PF laser trends).

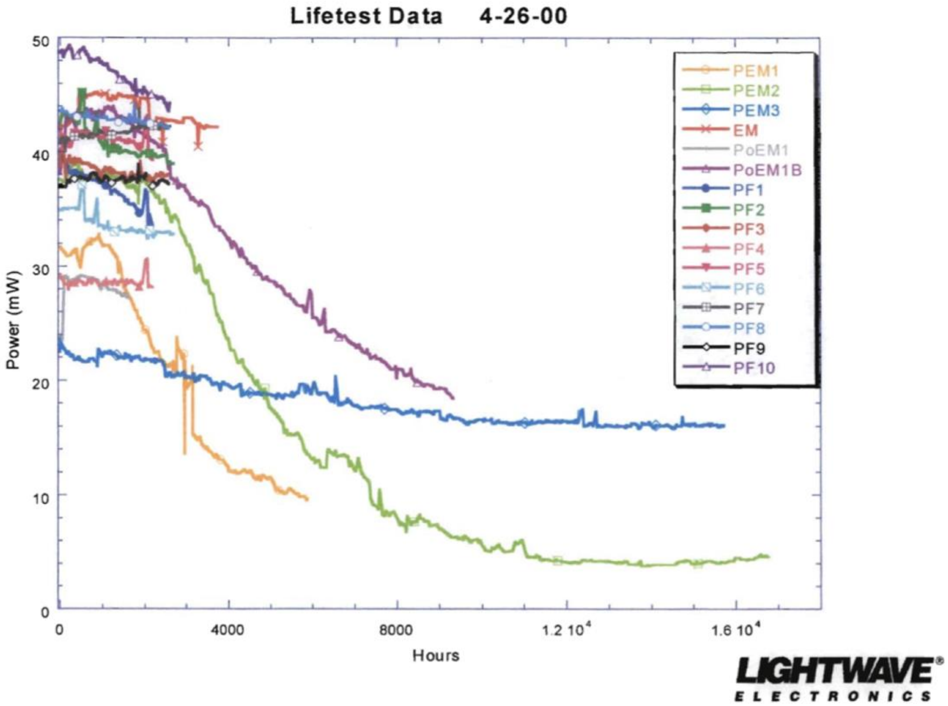

Figure 4. Lifetime Data from all lasers built in the TES Flight Laser effort showing longer trending on Pre-PF units.

2. LASER LIFETIME DATA

2.1 Brassboard laser test data

After vibration and thermal cycling tests on the two Brassboard lasers, both lasers were put on a non-accelerated life test. BB1 started life testing in February 1996, and BB2 started life testing in December 1996. Therefore, both lasers have been on life test for over 22 years on the ground, in laboratory settings, although they have been moved to different rooms on lab three times during life testing.

BB1 fiber output (FMON) power dropped steeply for 3 years into the life test and then increased slightly over the next 3-4 years before settling in to a slow decline. See Figure 5: Plot of computer-collected BB1 life test data (up until the data collection system failed), and Figure 6: Plot of manual data collection of BB1 life test data starting in 2002. Based on the change in degradation rate and the requirement to produce at least 10μW, BB1 lifetime was extrapolated to at least 12.5 more years from the time of the extrapolation in mid-2009. From Figure 5, note that the degradation signature is very similar to that seen in the early engineering models. Also important to note is that the BB1 laser diode power monitor or DMON from Figure 6, has declined, but at a much slower rate than FMON and LMON. Between February 2005 and May 2005, the normalized DMON signal dropped from 88% to 77%, exhibiting a failure according to the laser diode accelerated life test criteria of dropping below 80%, but still providing enough power that the FMON signal was adequate to meet TES science collection requirements. DMON signal data was not collected prior to March 2004, except for the initial value from February 1996 used as the normalization factor.

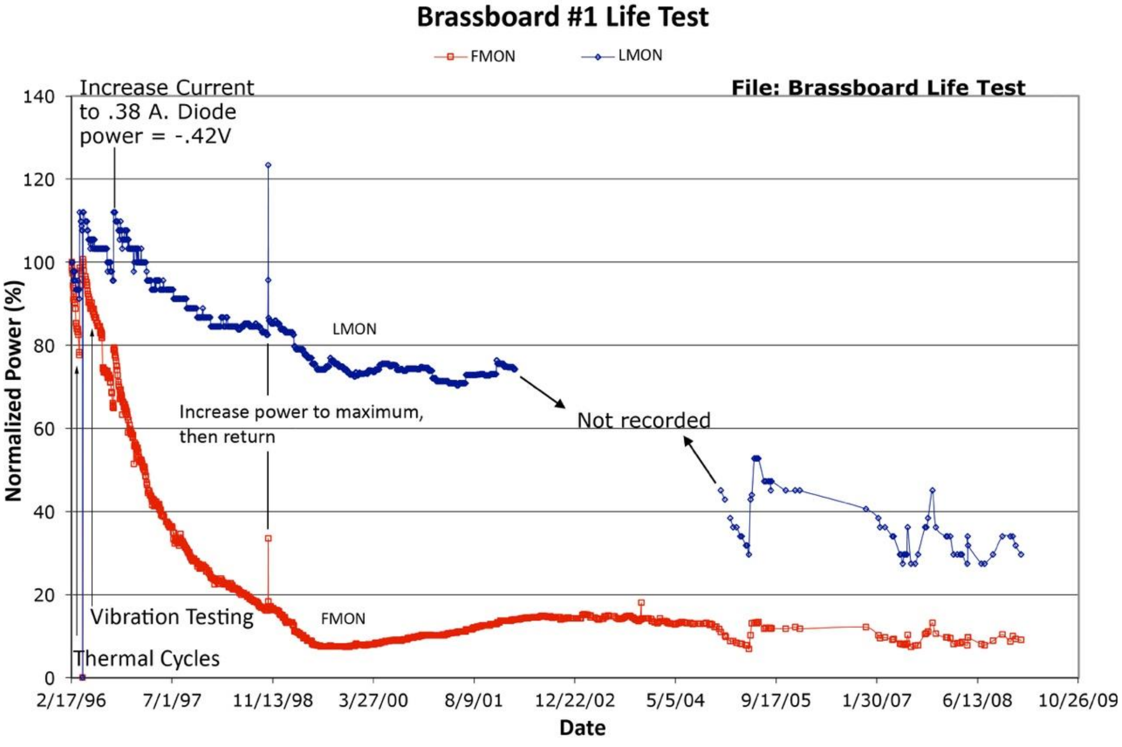

Figure 5. Computer-collected Brassboard #1 life test data (Normalized LMON and FMON power vs. Time)

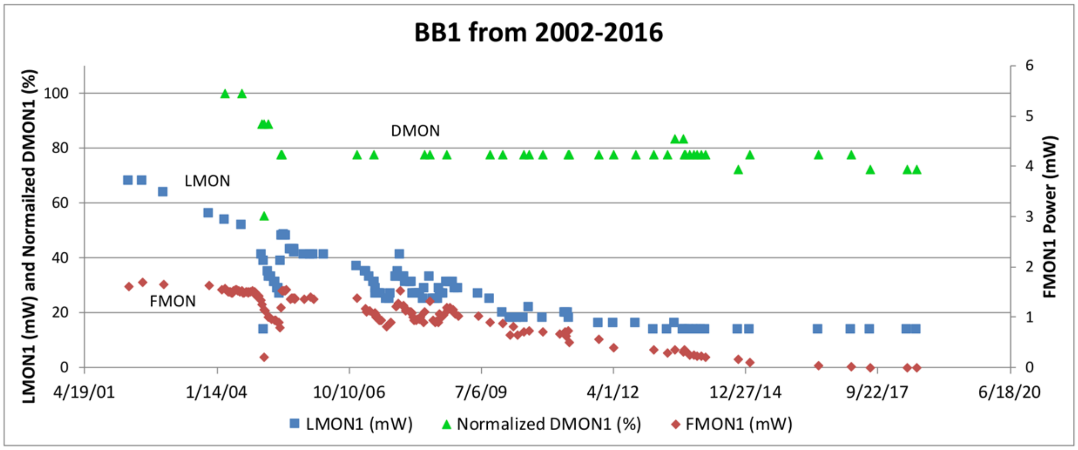

Figure 6. Manually collected life test data for Brassboard #1 (Normalized DMON, LMON, and FMON vs. Time)

BB2 gradually increased in power for about 2 years into the life test, then slowly declined for about 3 years before dropping suddenly, and then leveled off before being taken off life test to support instrument tests. Neither DMON nor LMON was recorded during the time of the sudden drop, making it difficult to diagnose the problem. When it was returned to life test, the output power had increased, but had started a more steep decline than before it was removed from life test, eventually starting to level out after about 2 more years and settling into a slow decline since then. See Figure 7: Plot of computer-collected BB2 laser life test data (up until the data collection system failed), and Figure 8: Plot of manual data collection of BB2 data starting in 2002. DMON was not recorded prior to March 2004, except for the initial value from December 1996 used as the normalization factor. The normalized BB2 DMON has varied between 100% and 80%, but the trend has been stable from 2004 through 2018, and has not met the criteria for laser diode failure.

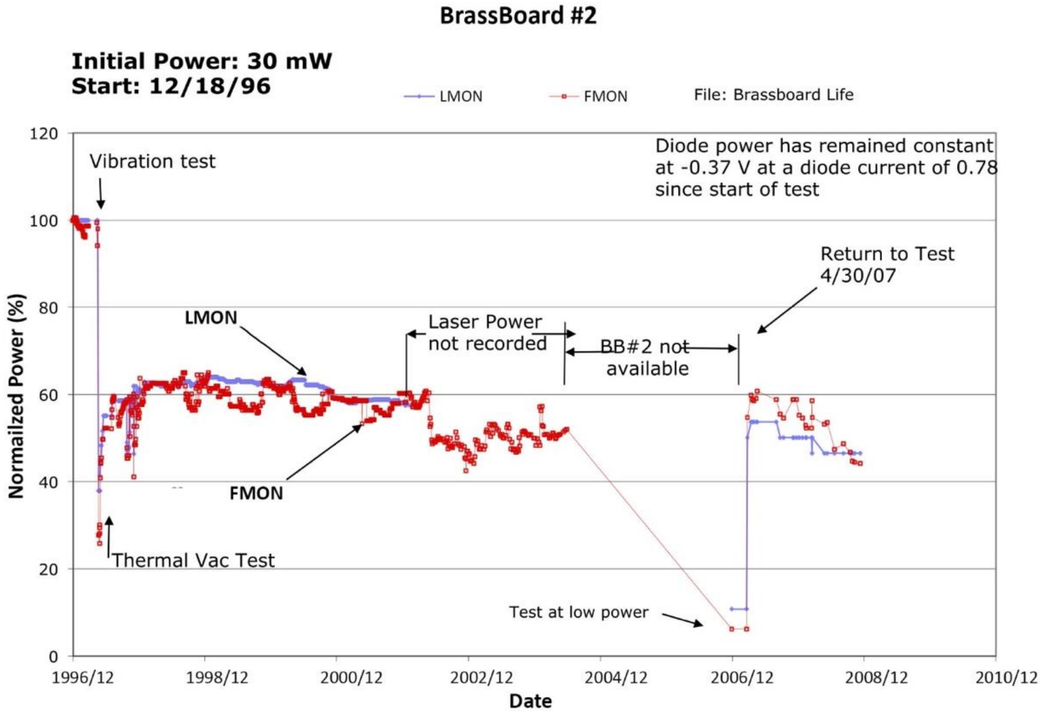

Figure 7. Computer-collected Brassboard #2 life test data (Normalized LMON and FMON power vs. Time)

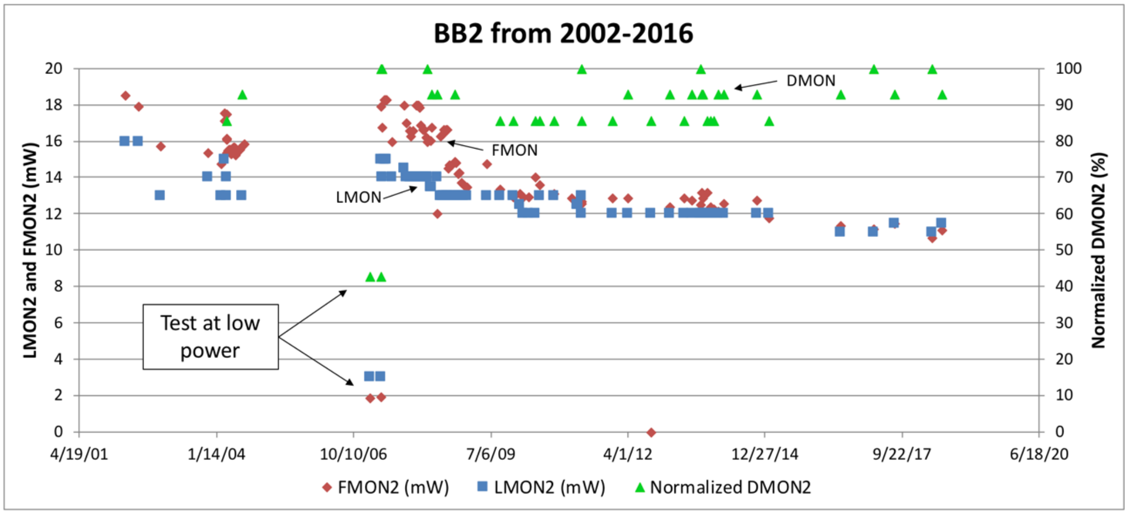

Figure 8. Manually collected life test data for Brassboard #2 (Normalized DMON, LMON and FMON vs. Time)

2.2 TES Laser A flight data

TES Laser A was the first laser to be used in flight and provided sufficient power for science observations for almost 10 years. On July 9, 2014, the power suddenly dropped so low that it seemed as though the laser had experienced a sudden, catastrophic failure, so Laser A was turned off and Laser B was turned on. No spacecraft events occurred close to the sudden failure of Laser A, so the hypothesis was that the pump diode had experienced a sudden, random failure. Laser B was then turned on for the first time and that data will be discussed in the next section, but when Laser B power dropped below what was useable for science collection about 2 years after initial turn-on, Laser A was turned back on just to see if it had any output. Unexpectedly, the Laser A pump diode turned back on with almost the same power (DMONA) it had before the sudden power drop two years prior. However, the 1064nm output from the Nd:YAG NPRO (as measured by LMONA and FMON) was less than a third of the expected value for the applied diode drive current and observed DMONA. See Figure 9 for the trends of the Laser A power monitors over the mission life. LMONA and FMON were approximately the same, so that indicates that the main reason for the power decline is not due to misalignment of the output fiber coupling. Possible causes of such LMONA and FMON degradation include a misalignment of the pump diode beam into the NPRO, a shift of the pump diode wavelength such that it has moved off the peak of the Nd:YAG gain curve, or degradation of the Nd:YAG gain due to ionizing radiation.

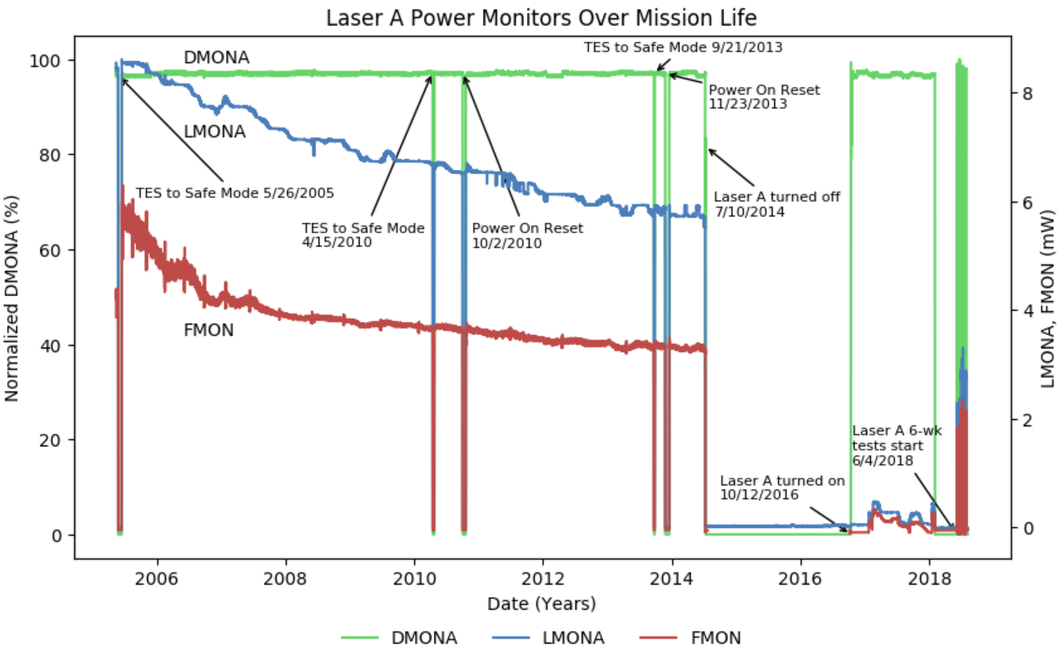

Figure 9. Laser A power monitor telemetry (Normalized DMONA, LMONA, and FMON) for complete TES mission.

2.3 TES Laser B flight data

Laser B was turned on July 10, 2014, after the suspected failure of Laser A. Laser B FMON power at turn-on was much lower than pre-launch after having been a cold spare for almost 10 years. The output power was fairly stable for about a year and a half after turn-on, but then started to decline, and unlike Laser A, the diode seemed to be gradually failing, as indicated by the pump diode power monitor, DMONB, declining along with the LMONB and the FMON monitors. DMONB also has shown a strange, unexplained behavior of sharp variances and the signal dropping suddenly (just after turn-on in July 2014 and again in March 2015) while no change was observed in the LMONB or FMON signals. However, the variances ended after that second sudden drop, and DMONB followed the declines of LMONB and FMON thereafter. As the decline seemed to be accelerating due to the accelerating degradation of the pump laser diode, a plan was developed to try and preserve as much laser life as possible. A laser power management strategy was implemented in September 2015, and consisted of turning the diode current down such that there was still enough laser power to collect science for about 2 weeks before needing to increase the diode current. Since diode laser wear-out failure is accelerated with higher drive current, the hope was to extend the laser life for at least 6 more months, so that the TES instrument could participate in a series of observations coordinated with other instruments on orbit. Using this laser management strategy, the laser output was sufficient for science collections for 10 more months. See Figure 10 for the Laser B power monitor trends over its operating life. The plot shows the decline of DMONB as well as the effect of the laser power management strategy.

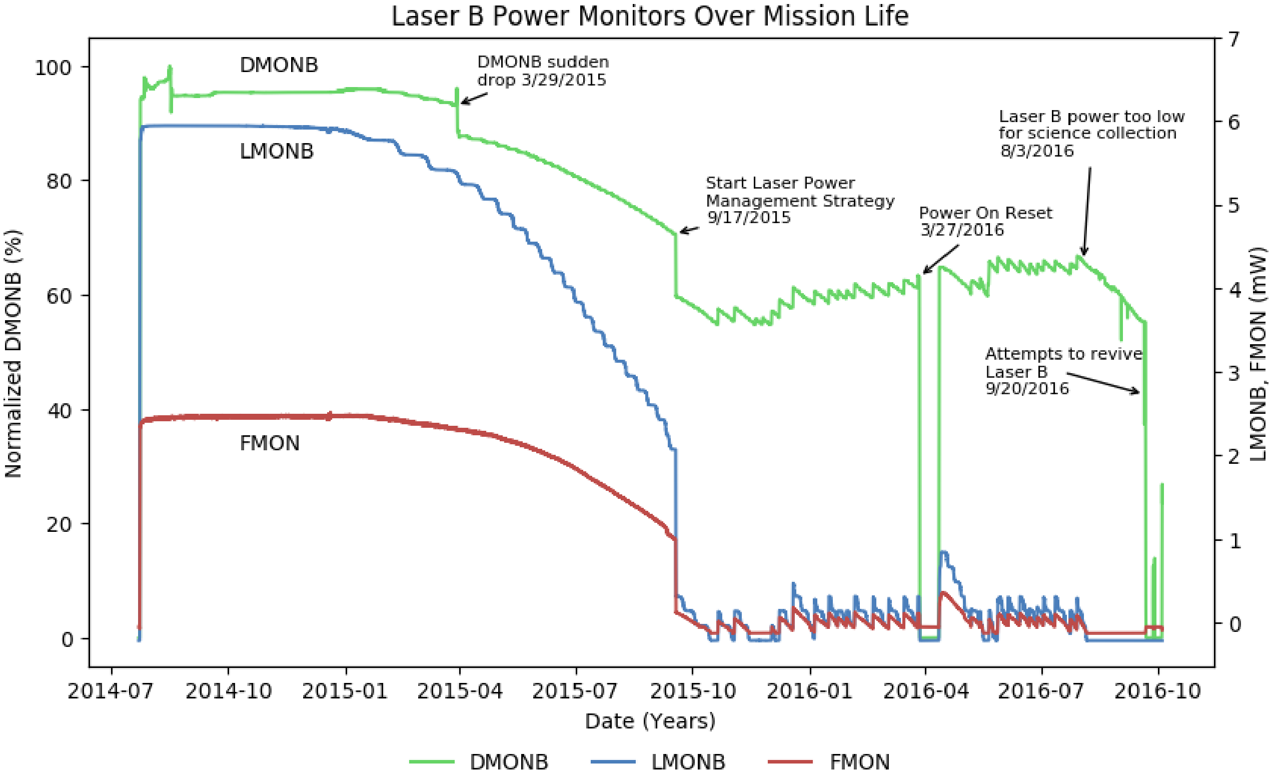

Figure 10. Laser B power monitor telemetry (Normalized DMONB, LMONB, and FMON) spanning its operating life.

3. COMPARISON OF LASER LIFETIMES

3.1 Pump laser diode lifetime: prediction vs. observed life on-orbit and on the ground

This long life laser data on the pump laser diode (DMON) presents a unique opportunity to compare actual laser diode life observed on-orbit and on the ground with the MTTF estimate (~27 years) generated from the laser diode accelerated life test data. The pump diode monitor (DMON) telemetry from the flight lasers shows that the Laser A pump diode did not fail or even drop appreciably in power over the 11 years of operation in space, despite the anomaly on July 9, 2014 that made it appear as though it had failed.

DMON telemetry from flight Laser B shows that its pump diode started to fail around February of 2015, and officially dropped below the failure criteria of 80% of original power around May of 2015 for a lifetime of 10 months according to the 80% criteria. However, the Laser B pump diode produced sufficient pump power for an FMON level adequate to collect science data through the end of September 2016, so using the mission power requirement, the observed lifetime for the Laser B pump diode was 2.2 years.

The ground-based data on the Brassboard life test units shows that the pump diode in BB2 has not failed over its 21.75-year life test so far, and that the BB1 pump diode is still functioning at 70% of its original power after 22.5 years on life test, having “failed” according to the 80% criteria after 9.2 years on life test. See Table 1 for a summary of observed pump diode lifetimes. An interesting finding when comparing lifetime results is that the pump diode that failed earlier than expected was the one that had been non-operational in the space environment for 10 years before its first turn-on. Either something about serving as a cold spare in the space environment for 10 years affected the laser diode adversely, or the laser diode was defective from the start, with the defect going undetected during screening. Investigation and analysis of that on-orbit laser diode failure could be the subject of a future paper.

Table 1. Summary of observed pump diode lifetimes for flight lasers and ground life test lasers against two failure criteria and estimated MTTF from accelerated life testing.

	Observed Lifetime (yrs)	**Observed Lifetime (yrs)**
Pump laser diode:	80% criteria	Mission Criteria
Flight Laser A	11+	11+
Fiight Laser B	0.8	2.2
Brassboard #1	9.2	22.5+
Brassboard #2	21.75+	21.75+
Accelerated life test estimate (80% criteria)	27 years	

3.2 Model 125 laser system observed lifetimes: ground vs. space

The long life laser data presented in this paper also allows a comparison between the observed ground and space lifetimes of the more complex, multi-stage Model 125 laser system. The lifetimes for the two laser systems being life tested on the ground and the two flight laser systems on TES are observed by monitoring the fiber output, FMON, over time. The two ground-tested lasers are still running, resulting in demonstrated lifetimes of 22.5+ years for BB1 and 21.75+ years for BB2. In comparison, over the 14 years of the TES mission, Laser A demonstrated a lifetime of more than 11 years in space (it was still producing more than adequate FMON for science operations at turn-off), and the observed lifetime of Laser B was 2.2 years after spending 10 years in space as a cold spare.

4. CONCLUSIONS

4.1 Conclusions

The data from non-accelerated life tests of LWE Model 125 lasers has been presented from over 20 years of on-going ground-based life tests as well as from 14 years of space-based laser operations. Flight Laser A successfully enabled TES instrument science data collection for more than twice the required mission life of 5 years (and more than four times the required laser life). Not only has this data allowed real-time laser diode lifetime measurements that can be compared with accelerated life test estimates, but it has also allowed lifetime comparisons between full multi-stage laser systems operating in space with those operating on the ground. Without a controllable, predictable way to accelerate life tests of complex, multi-stage hybrid laser systems such as the Model 125 laser, the only way to demonstrate long laser lifetime in space is to collect long-term life data on lasers actually operating in space. An added benefit of the lifetime data presented here is the access to and tracking of all three optical power monitors (DMON, LMON, and FMON), each from a different point in the laser optical train, for the ground-test lasers as well as the flight lasers. The differences in trends over time among the three power monitors provides insight into the failure mechanisms that could be causing observed declines as the lasers age. An investigation into the root causes of observed flight and ground-based laser degradations could be the subject of a future paper. Another lesson learned from this lifetime data is that the observed flight laser lifetimes would have been shorter had it not been possible to increase the pump diode current on-orbit to keep up with efficiency losses experienced in the pump diode for Laser B and in the NPRO gain for Laser A. This information provides guidance to future missions that have to make decisions regarding appropriate telemetry collection and contingency operations for handling laser degradation near end-of-life.

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