ABI Life Test cryocooler system 2025 update

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Abstract. The Advanced Baseline Imager (ABI) Pulse Tube Cryocooler System is a two-stage pulse tube cryocooler designed to service space applications requiring simultaneous cooling of two separate optical assemblies at different temperatures, ultra-high reliability, and long lifetime. The mechanical cryocooler is a two-stage variant of the Northrop Grumman HEC (High Efficiency Cryocooler), consisting of an integral linear coldhead and a remote coaxial cold head. This two-stage HEC was designed to provide simultaneous cooling power of 2.27W at 53K at the linear stage and between 5.24W and 8W at 183K at the remote stage. The Life Test Unit achieved 6.7 years of stable performance prior to the first ABI cryocooler launch on GOES-R, providing better instrument optimization for the mission. Since June 2018, the life test has been operating at an elevated rejection temperature with periodic returns to baseline to verify performance. As of May 2025, the ABI Life Test has been underway for 14.8 years, and the Life Test Unit has completed over 13.9 years of steady thermal performance (93.3% uptime). System performance has remained consistent long past mission requirement life with little degradation in cooling performance. The test has shown that there is some performance variation in beginning of life to end of life, however data indicates this variation is predictable. This paper presents the performance data collected on the life test cooler during acceptance testing and over the course of the cooler's life test and analyses the relevant performance parameters against predicted performance.

1. Cryocooler system introduction

The Advanced Baseline Imager (ABI) Pulse Tube Cryocooler System was developed as a two-stage configuration of the TRL-9 Northrop Grumman High Efficiency Coolers (HEC). As of this publication, no failures have been experienced by these systems, accumulating well-over three hundred years of cumulative failure-free operation, with some coolers achieving nearly 20 years of on-orbit performance.

The dual stage pulse tube cryocooler configuration features an integral linear coldhead and a remote coaxial coldhead. The benefit of such a design is the ability to provide simultaneously cooling of two optical sub-assemblies at different temperatures. This technology utilizes Northrop Grumman's high-reliability, non-wearing compressor design combined with pulse tube coldheads, featuring no moving parts at the cold end that could contribute to wear mechanisms. As such, these systems provide extended lifespans for missions requiring multiple years of operation and zero-maintenance.

The ABI Life Test Unit (LTU) was the first of twelve cryocooler systems that were delivered in support of the Advanced Baseline Imager (ABI) Program. The cooler was manufactured in 2006 and

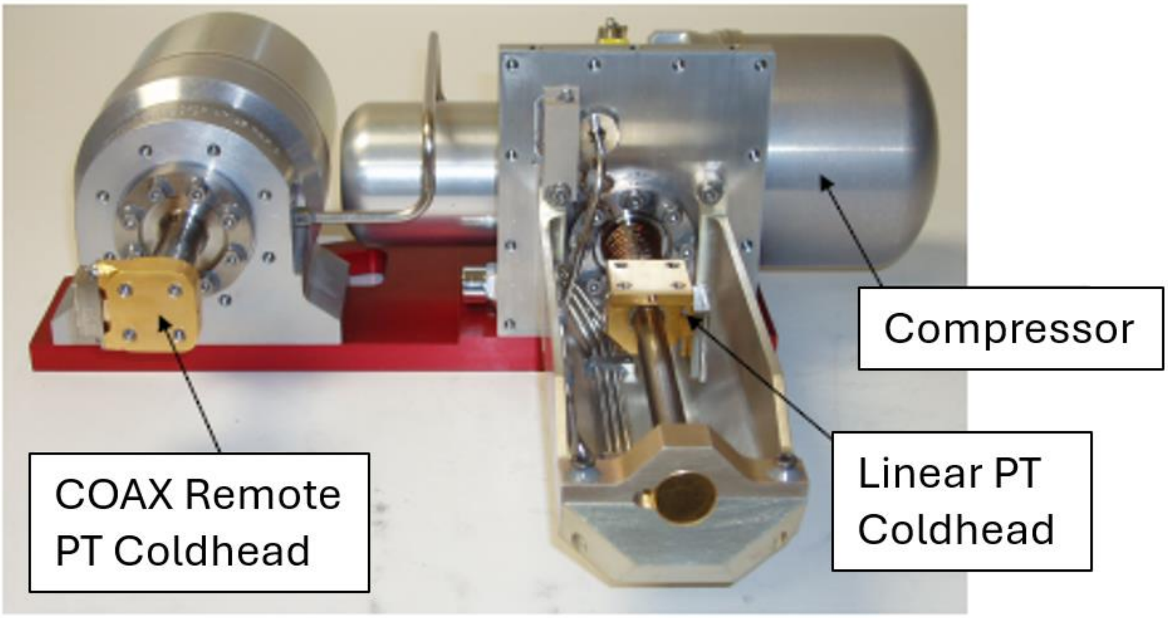

Figure 1. Advanced Baseline Imager (ABI) life test cryocooler, showing the parallel two stage coldheads. The baseline conditions for these coldheads are 2.27W of cooling power at 53K for the integral linear cold head (right), and between 5.24W and 8W of cooling power at 183K for the remote coaxial coldhead.

characterized during Acceptance Test Procedures (ATP) at Northrop Grumman, before delivery to L3Harris (formerly ITT). The results of the pre life test characterization were published in 2008 per Colbert et al [1]. Under their supervision as prime contractor, L3Harris managed the overall responsibility of the life test campaign – initial results were published [2] in 2012. This paper presents analysis of the cryocooler's ongoing performance nearly 20 years post-delivery, defines the key degradation mechanisms that occur over the unit's lifetime, and compares observed performance against predicted end of life (EOL) performance.

2. Test set-up description

2.1 Description of test configurations and test support equipment

The results summarized in this paper are meant to properly characterize the thermodynamic performance of the system over its specified lifespan. Of additional consideration are the combined effect of the aging control and drive electronics, provided by an Engineering Ground Support Equipment (EGSE) rack, used in place of the designed flight electronics, the Cryocooler Control Electronics (CCE). This will be discussed further in following sections.

The LTU was integrated into a vacuum chamber for the duration of its test campaign as shown in Figure 2. Mechanically, the LTU is mounted to a heat exchanger plate to maintain the required rejection temperatures at the integral coldhead heat rejection interface. A single recirculating lab chiller removes heat from both the integral and remote coldhead heat exchanger plates. Note that this chiller provided cooling for both rejection surfaces in series – since the dissipation for the integral coldhead is on the order of 3x larger than the remote coldhead, this configuration does yield a temperature difference between the reject temperature of each coldhead. As the temperature was controlled to the integral reject, the remote reject was held at a cooler temperature. The importance of this will be discussed in later sections.

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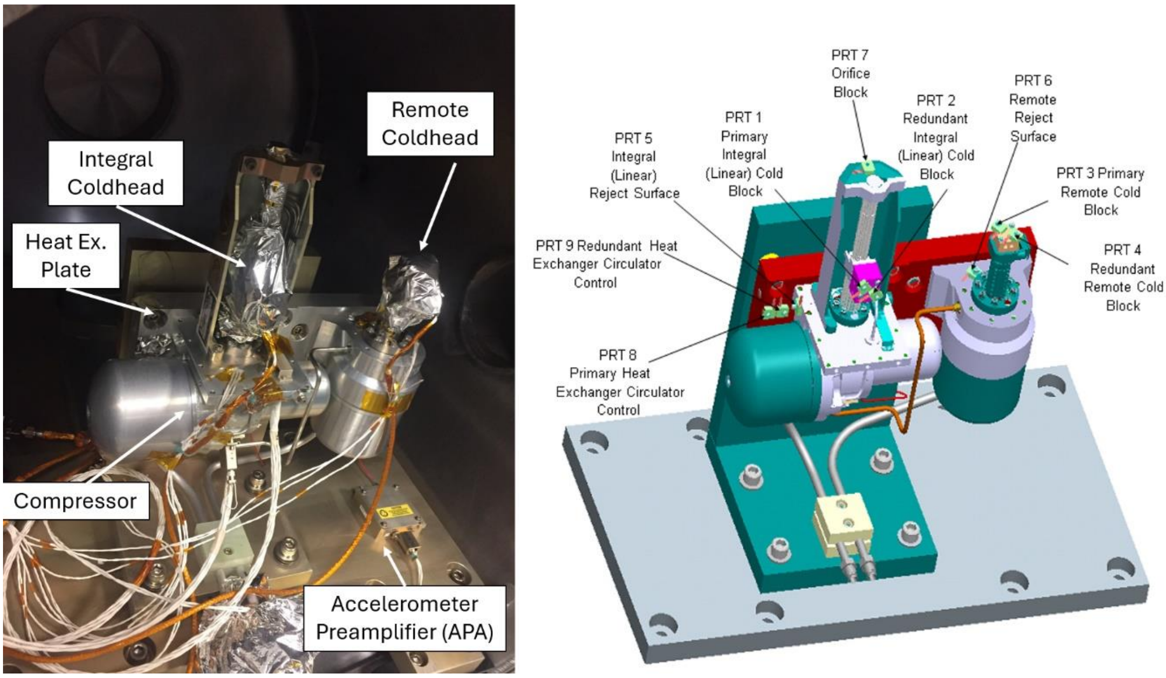

Figure 2. The Life Test TMU integrated into the vacuum chamber (left) and the locations of all Non-Flight PRTs installed on the Life Test TMU (right).

An EGSE (a lab grade cryocooler drive and control electronics rack, functionally equivalent to a flight CCE) provides the cryocooler drive signal, cold tip temperature control, and vibration control. The EGSE rack collects all telemetry collected during normal flight operations, such as primary and redundant PRT readings for coldhead temperature, thermistor readings for rejection temperature, motor drive, accelerometer signals used for vibration control, drive frequency, and more. The drive rack also maintains key hardware safety interlocks. Input power, current, and voltage are collected via a Valhalla 2400 power meter. Temperature telemetry at several additional locations on the cryocooler is provided by non-flight PRTs read by Lakeshore 218S, as shown in Figure 2.

2.2 ABI baseline specification and initial characterization

The ABI baseline operating conditions are as follows:

- 2.27W load at <53K for the linear coldhead
- Between 5.24W and 8W load at < 183.1K at the remote coldhead.
- 300K at the thermal mechanical interface for the TMU
- Optimum drive frequency between 60-65 Hz
- <143W total TMU input power

These specified operating conditions were first characterized by Northrop Grumman in the initial ATP test campaign. First, a drive frequency optimization was performed and found the optimum to be 61 Hz. Load maps were generated at several remote and integral coldhead heat lift values and input power levels at reject temperatures of 253K, 300K, and 313K. These loadmaps are shown in **Figure 3**. The cooler's performance was also characterized in several different orientations (coldheads down, coldheads at 45°, etc). For additional details on this characterization, refer to Colbert et al [1]. This performance characterization will be referenced as the beginning of life metrics to which this report will compare the end of life mapping at the conclusion of the lifetest.

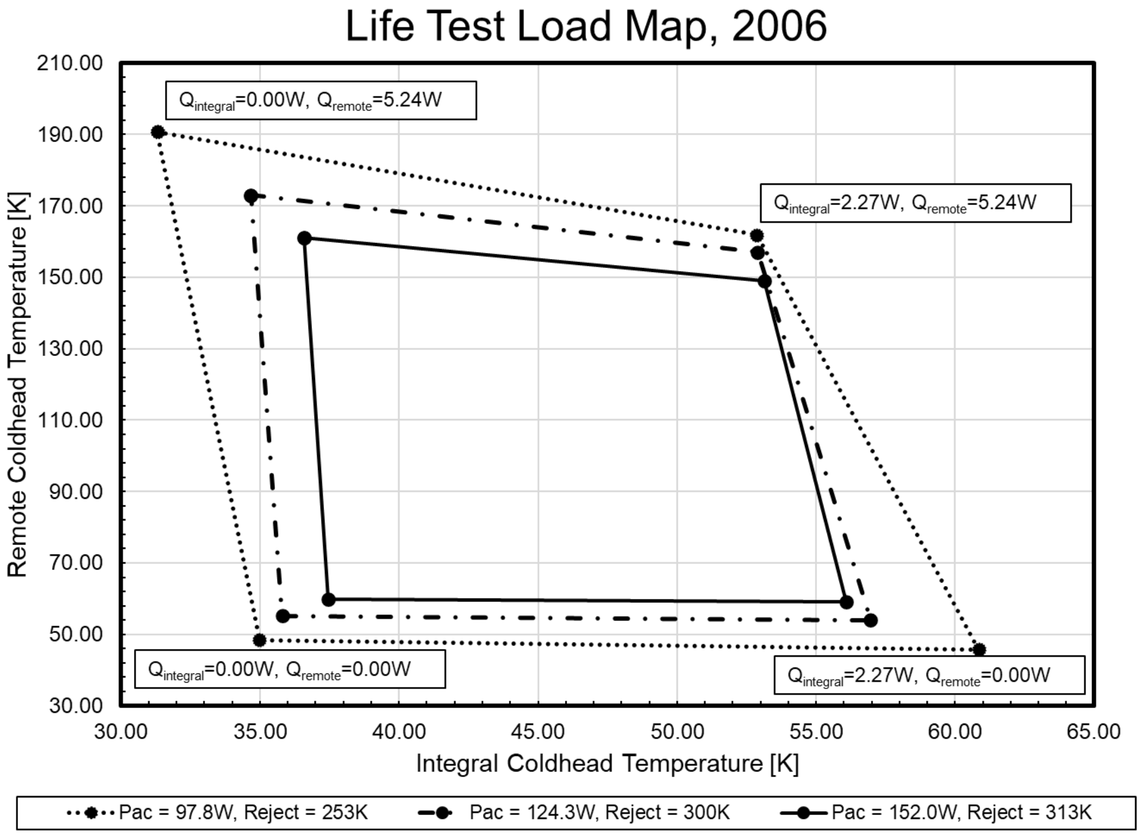

Figure 3. Initial Characterization Testing Loadmap

For ground testing, the baseline orientation is with both the linear and remote coldheads pointed upward, as shown in Figure 2. This configuration was chosen because the linear coldhead parasitic loads are most representative of operation in an on-orbit 0g environment. The warm end of each coldhead is the opposite direction, as the coaxial design directs the flow downward towards its reservoir, while the integral pulse tube and orifice are in-line upwards. The remote coldhead is subject to higher parasitic loads since it's cold end is upward, but the relative impact to overall system level performance is lesser and thus is acceptable. The long term thermal testing at L3Harris has been completed in the single baseline orientation, with both coldheads pointed upward.

3. Cryocooler life considerations

Cryocooler system level reliability and lifetime are often key drivers for reducing mission level risk and thus must be given careful consideration. Cryocooler lifetime degradation mechanisms can be broken into two categories: those that impact the cryocooler control electronics (CCE), and those that impact the thermomechanical unit (TMU). The CCE degradation mechanisms will only be discussed briefly, as the focus of this body of work is on the TMU.

3.1 Thermomechancial unit (TMU) lifetime considerations

The design of the HEC cryocooler mitigates or eliminates many of the common mechanisms that contribute to reduced life in other cooler systems. The compressor ultizes dual opposed linear motors with flexure bearing pistons that allow for the elimination of the piston rub and minimized off axis loading. This also ensures the compressor does not wear during stop/start cycles, and thus can achieve an infinite number of stop/start cycles. Both integral linear and remote coaxial pulse tube coldheads feature no moving parts, eliminating potential wear mechanisms in the coldhead. As such, the leading contributor to performance variation in the TMU is the loss of the working fluid that the unit is charged with during BOL.

The compressor, while hermetically sealed, is not a fully welded assembly and thus leaves small leak paths for the working fluid. These are on both sides of the centerplate, where the endcap cover and reservoir are installed, the coldhead mating flanges, and various conical metal seals in the transfer lines. All other interfaces of the system are welded and verified helium leak tight. At the reservoir, motor cover, and coldhead mating flanges, metal crush seals are integrated to achieve a hermetic seal without permanently sealing the TMU. These seals achieve a leak rate $\leq 5.5 \times 10^{-7}$ mbar-Liters/sec, specified for a minimum of ten years of operation without a significant degradation in performance. This accounts for 5 years of ground storage and up to 5 years of on-orbit storage. In total, these coolers are designed to remain charged for 20 years without loss of performance.

A leak rate of this magnitude would contribute to losses of roughly 1.3 psi every 5 years. The ABI LTU is estimated to have lost 5.2 psi of its 515 psia fill pressure, a reduction of ~1%. The resultant effect is a 1.39% increase in compressor input power to match BOL performance at the same conditions (IE, slightly more stroke is required to achieve the same acoustic power), well within the design constraints of the compressor. This comparison is shown graphically in Figure 5.

3.2 Cooler drive electronics life considerations

Of additional consideration is degradation in the drive and control electronics. End of life variations such as radiation (the largest contributor), temperature delta, and ageing are determined for each component within the cryocooler electronics and applied along with the initial tolerance to predict EOL performance. Mitigations such as part selection in accordance with proper derating requirements are specified. The efficiency loss due to electronics degradation is assumed to be a 5% decrease. More information can be provided upon request. Calculated EOL performance fulfils all performance requirements, allowing for a reliability of >90% at 87,600 hours (10 years) of operation. Note that for the Life Tests, the Valhalla 2400 power meter is placed downstream of the EGSE and thus the recorded changes in input power are reflective only of changes to the TMU. Emulation of the CCE flight electronics with an EGSE is therefore adequate for predicted performance degradation for the purpose of the life test.

4. Long term thermal testing

4.1 BOL vs EOL baseline performance

The unit began the L3Harris Life Test on June 12, 2009. As of May 18, 2025, the test campaign has spanned a total of 5429.37 days of operation, with a total uptime of 93.3%. This equates to 13.9 years of cumulative operation and 19.8 years since manufacture.

Baseline performance, in the form of load lines, has been measured throughout operation, and compared to the BOL results found during Northrop Grumman's ATP. In general, all thermal performance has been steady within expected bounds during each system evaluation. Figure 4 shows an overlay of thermal performance mapping, in the form of two representative load lines, collected at BOL and EOL.

The change in integral cold tip temperature is attributed to two things: performance degradation over the unit's lifetime, and changes in the test setup between the Northrop Grumman ATP and the L3Harris Life Test. As discussed in the earlier section, the test setup at L3Harris using a single serial chiller loop to cool both heat exchanger interfaces. This contributes to a small temperature increase (~3K) from the integral to the remote rejection surface temperatures, where the remote coldhead reject

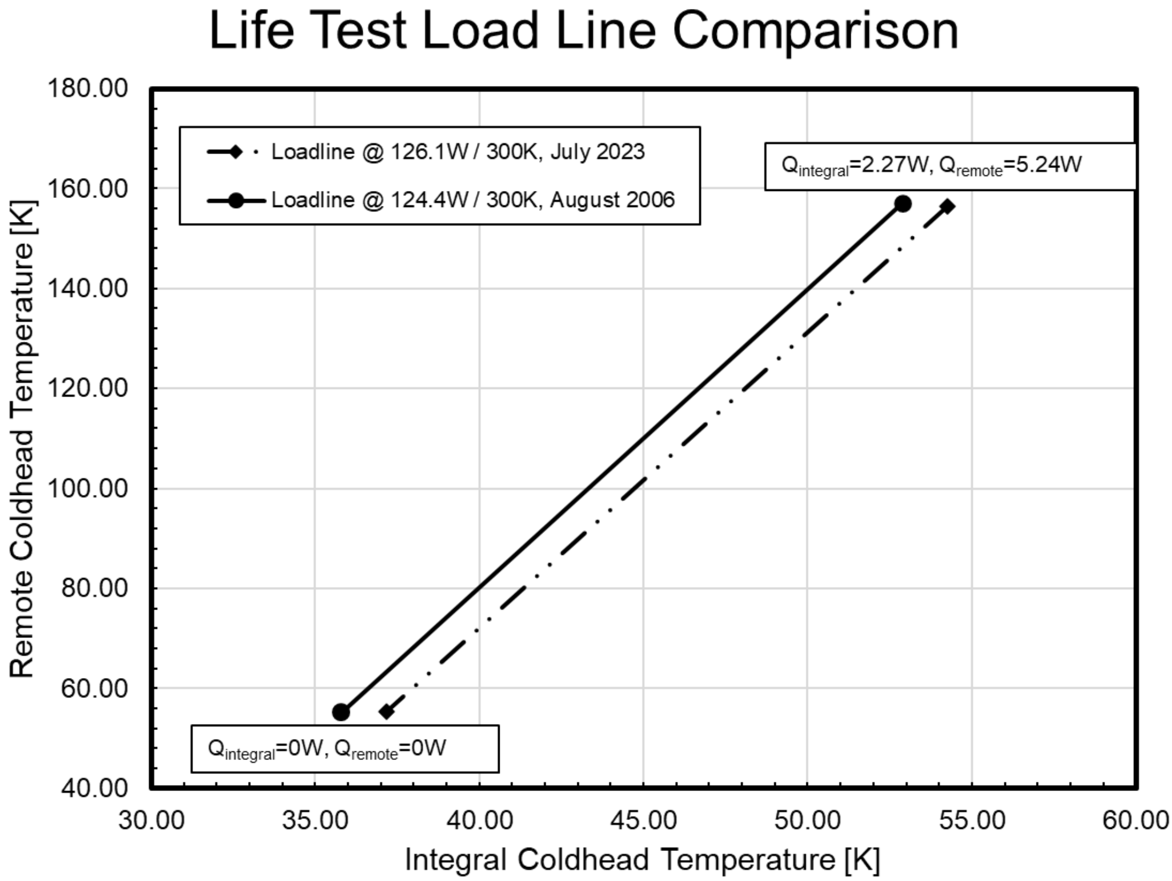

Figure 4. Load line comparison between Life Test TMU ATP in 2006 and data collected in 2023 at the same conditions.

sits at a cooler temperature. As shown by Figure 3, when the remote coldhead is warmer due to having heat load applied to it, the integral coldhead is able to achieve lower temperatures for the same cryocooler input power and integral coldhead heat lift. The underlying driver for this effect is that, when warmer, the remote coldhead is operating in a less resonant condition and thus consumes less of the total acoustic power that is split between the integral and remote coldhead. This leads the integral coldhead to consume more power, leading to colder cold tip temperatures. Conversely, when the remote coldhead is cooler, it is more resonant and thus consumes more of the total acoustic power. This effect is observed in Figure 4 , where the 3K lower rejection temperature for the remote coldhead leads to the remote coldhead consuming more acoustic power and a resultant warmer temperature at the integral linear coldhead. Analytical modelling and test data suggest that this difference in reject temperature contributes ~25% of the observed increase in integral cold tip temperature for equivalent input power and heat load. The remaining 75% of the total increase in integral cold tip temperature is attributed to the predicted lifetime degradation corresponding to an HEC that's been charged for 19 years and operating for ~14 years. The primary lifetime degradation mechanism for the HEC is gradual loss of working fluid, which is discussed previously in Section 3.

Figure 5 shows an overlay of a BOL dwell, tested during Northrop Grumman ATP, and an EOL dwell collected in 2023 at L3Harris. Overall, the cooler easily satisfies it's expected performance metrics at 19 years of life, with a small power increase of 2.20W, slightly above the predicted 1.73W increase at baseline conditions. This discrepancy is most likely due to variation in operating pressure, thus leak rate, driven by extended operation at hotter reject temperatures than were originally baselined.

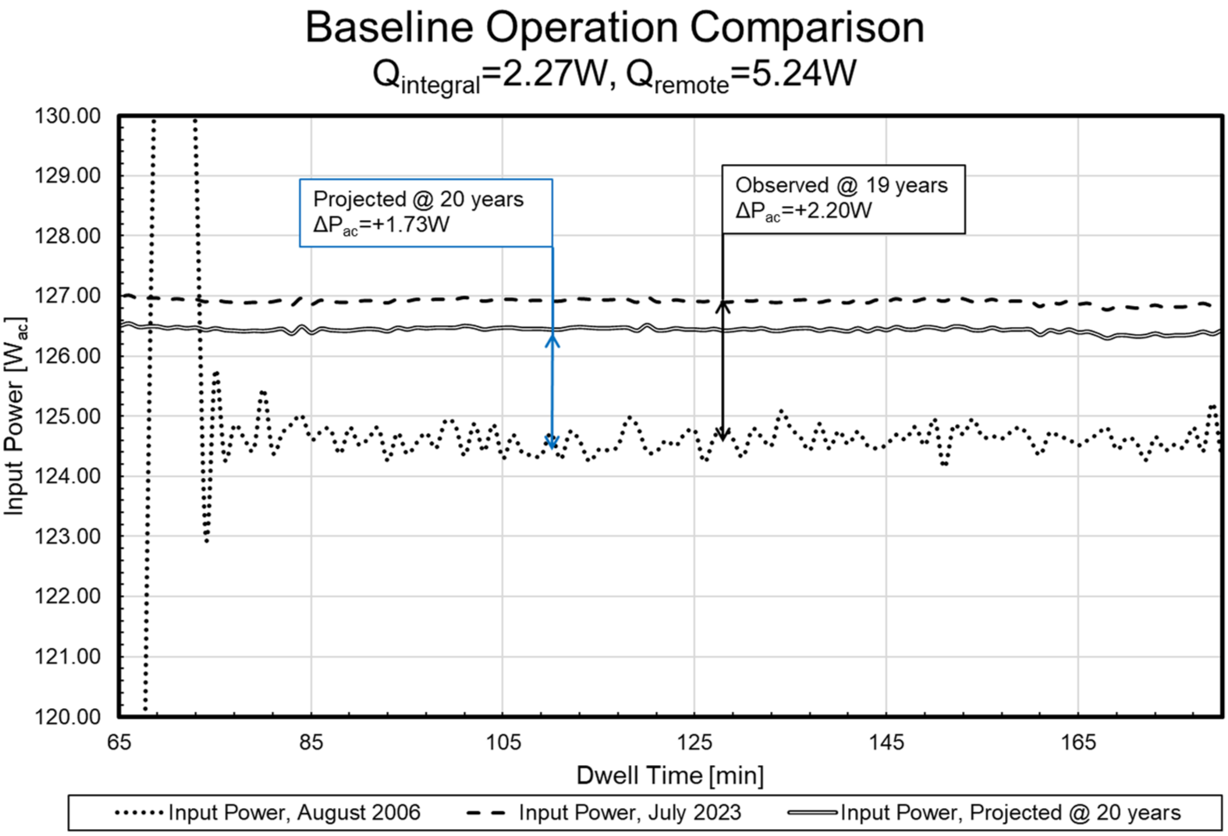

Figure 5. At baseline conditions, performance of measured Beginning of Life and End of Life required input power compared against projected End of Life required input power (as measured by Valhalla 2400 power meter minus cabling losses).

4.2 Off-Baseline environmental conditions and cooler power cycling

Since June 2018, most the cooler's operating hours have been at an elevated rejection temperature of 330K, with occasional returns to the baseline condition at 300K to check for any changes in performance. Such conditions will contribute to higher leak rate, as cooler operation will experience elevated operating pressures. Since the inception of the high-temperature test, cooler performance has remained anchored to expected metrics. Due to the selection of coefficient of thermal expansion (CTE) matched components, performance atrophy via leak rate is purely a function of operating pressure and not seal joint separation.

Table ***1*** displays the LTU heat rejection temperatures and total operational time incurred during test, as a percentage. This demonstrates a key advantage of the pulse tube and non-wearing compressor design. Several years of consistent operation at this elevated condition showcases the remarkable reliability and robustness of the cooler system.

Over the course of the life test, multiple instances of cooler power cycling have occurred. As of May 18, 2025, there have been 293 cooler on/off cycles, with no indications of impact to performance. Figure 6 shows these power cycling events, with a return to baseline performance after each cycle.

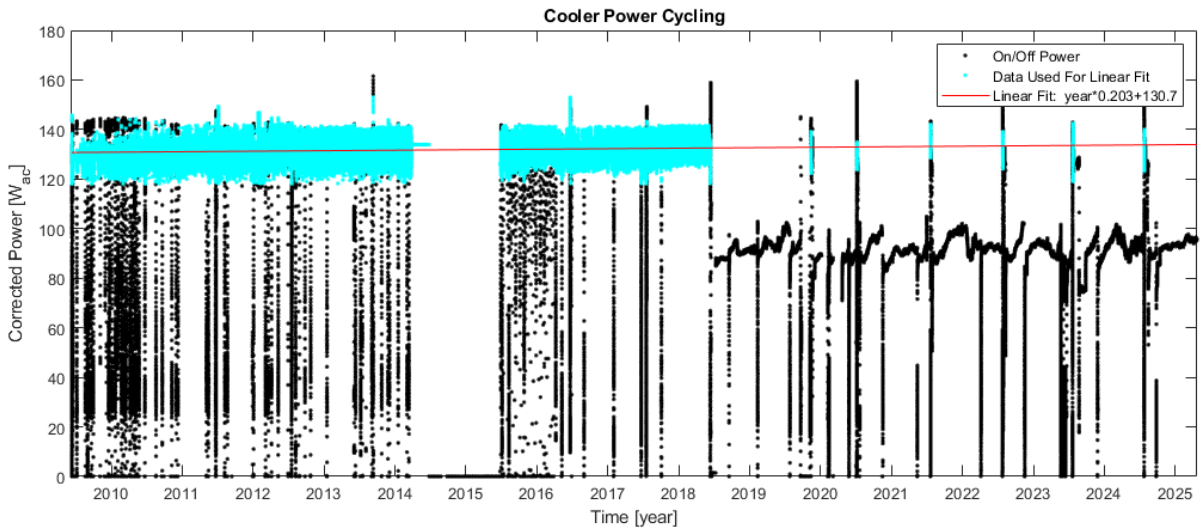

Figure 6. Cooler power cycling and total uptime to show a fit of input power (as measured by Valhalla 2400 power meter minus cabling losses) to achieve baseline operation as a function of time. As shown in teal, input power levels during startup / shutdown and during the reduced input power, elevated reject temperature operation are omitted from the fit. The gap in 2015 is attributed to the shutdown of the life test to relocate the unit from Indiana to New York. The "years" variable in the curvefit equation corresponds to total runtime in years.

Table 1. Uptime at Operating Conditions.

Operating Condition	Baseline Specification	BOL	EOL	Off-Baseline Condition
Integral CH Temperature	<53K	52.8K	54.25K	76.05K
Integral Heat Lift	2.27W	2.27W	2.27W	2.27W
Remote CH Temperature	<183.1K	157.03K	156.45W	113.27K
Remote Heat Lift	5.24W	5.24W	5.24W	2.0W
Integral Reject Temperature	300K	300K	300K	330K
Operating Frequency	60-65Hz	61Hz	61Hz	61Hz
TMU Input Power	<143W	124.4W	126.1W	93.05W
Total Uptime	---	~8 years		~6 years

5. Conclusion

As of May 2025, the ABI Life Test has been underway for 14.8 years, and the Life Test Unit has completed over 13.9 years of steady thermal performance (93.3% uptime), including time at off-nominal elevated rejection temperature. Test environment, not cooler performance, has been attributed to the

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multiple stop/start events preventing the achievement of 100% total uptime. The main wear mechanism, leak rate, has been mitigated in the TMU design, and end of life assumptions have been well characterized. In total, the ABI LTU has achieved an EOL performance in line with predictions, even when exposed to stressing operating conditions, such as the 330K rejection temperature.

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