THERMAL VACUUM TESTING OF A MODIFIED COTS CAMERA FOR USE IN LUNAR ENVIRONMENTS

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ABSTRACT

The primary objective of this study was to simulate lunar thermal environments to qualify a modified Commercial-Off-The-Shelf (COTS) camera for potential flight applications. A comprehensive testing regimen was developed, including both vacuum and thermal vacuum testing. The tests subjected the camera to temperatures corresponding to expected extrema, and thermal performance was recorded throughout the process. The testing demonstrated that both the camera and its thermal protection systems were able to maintain operational functionality under most of the simulated conditions. The results of the testing indicate that the implemented thermal protection system is effective for the expected lunar environments. Despite the decrease in operational time in comparison with terrestrial usage, the camera's overall performance supports its suitability for use in both flight and lunar missions.

Figure 1: Ed White with a Hasselblad Camera on Gemini 4. (Williams, 1965)

INTRODUCTION

Cameras, both still and video capable, have had a long history in space flight. A relatively well-known manufacturer of cameras, Hasselblad, had their first camera flown on Mercury 8 in 1962. These cameras were modified from their off-the-shelf form factor specifically for spaceflight, usually by removing excess weight and allowing for a higher capacity of photos to be taken. The higher quality photographs allowed for data collection and created many of the iconic photographs associated with early space flight. During the 67 hour lunar stay of Apollo 15, over one thousand pictures were taken using modified COTS cameras.

The lunar thermal environment has become a topic of increased study in recent years, as NASA's workforce prepares to return humans to the moon. Thermal protection of tools and equipment can be difficult due to the lack of atmosphere, extended days and nights, and problematic regolith of the lunar surface. To protect hardware from these hazards, various Thermal Protection Systems (TPSs) and Thermal Control Systems (TCSs) have been developed and subjected to testing. For the Handheld Universal Lunar Camera (HULC), the TPS is a multi-layer blanket, designed to protect from both dust and the highly transient thermal environment.

This paper looks to outline the thermal testing approach of a modified COTS camera in anticipation of use for early Artemis missions. A brief overview of the design process, the testing results, and model correlation and predictions will be covered.

METHODOLOGY

The camera selected for this study was the Nikon Z9 Full Frame Mirrorless camera. This model was released in late 2021 and included upgraded features for autofocus and continued shooting. Multiple cameras from different manufactures were considered early in this project, but the Z9 was down selected as a result of a previous trade study. Significant changes to the firmware of the camera specifically for this project allows for improved camera operation with respect to space missions. This paper will focus instead on the hardware changes, TPS, and resulting operations in TVAC.

Hardware modifications of the Z9 camera included the addition of a bottom mounted handle to allow for gloved operation. The handle includes large capacitive buttons, a remote flash controller, and mounting hardware for quick attachment to astronaut tool belts. Initially, the handle was planned to be 3D printed out of Ultem, but due to cost, may be spun in AL6061 for future revisions. The handle also includes a bracket for a sapphire view screen that protects the Z9 LCD screen, as well as attachments for the thermal blanket.

Surrounding the camera during EVA missions is a thermal blanket. This blanket consists of a 7-layer MLI interior, encased in an Orthofabric shell. The blanket has an opening at the bottom, which is rolled to be closed, similar to a dry bag roll top enclosure system. The form factor of the blanket is custom fit to the geometry of the camera to provide an appropriately tight but not tensioned fit. Seams are sewn in a way to prevent dust passage, while also maintaining some level of

Figure 2: Thomas Pesquet Testing the HULC in its Thermal Blanket. (ESA, 2023)

radiation protection. Hook and loop mount points are generally sewn only to the external layer of the Orthofabric, as well as any button markings, to reduce impacts on MLI performance due to layer compression.

Vacuum testing occurred in facilities located at Marshall Space and Flight Center in Huntsville, Alabama. For vacuum only testing (no thermal control), the recently opened HiTEMP lab was used. Tests ran here include storage card characterization, IVA simulation, and video settings characterization. Thermal vacuum tests, intended to push the camera to simulated lunar thermal environments, was performed in a shrouded vacuum chamber in MSFCs Environmental Test Facility (ETF). The configuration of the camera was dependent on the environment being tested. For IVA use, the camera was used without a blanket or grip, as IVA use will be ungloved. Tests included extended video recording, basic photography cycles, and charging of a battery. For EVA use cases, the camera was installed in a blanket and subjected to various simulations of astronaut use. An image showing the HULC in a TVAC chamber is shown in Figure 3.

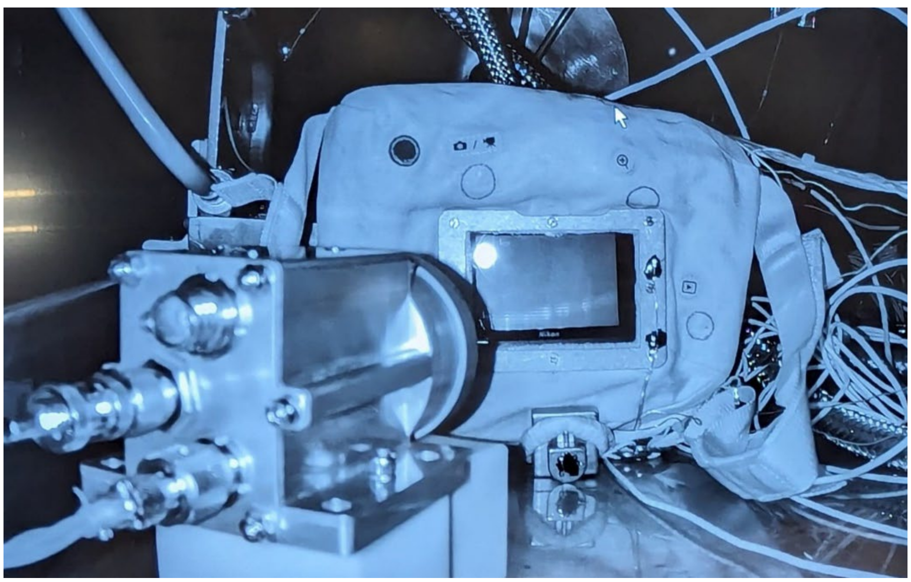

Figure 3: The HULC undergoing TVAC Testing at MSFC.

Thermal environments were determined using a Thermal Desktop (TD) model of the lunar surface for three main extreme cases. The location of Artemis III was used as the input for lunar latitude, and time of day was varied for hot and cold cases. A third case of a Permanently Shadowed Region (PSR) was calculated as well. To allow for testing in a thermal vacuum chamber, an equivalent shroud temperature was hand calculated using an energy balance method and verified by running steady state cases in TD. These values are given below, along with some assumptions used in the analysis. Surface temperatures were calculated using data pulled from the Diviner Orbiter and averaged over a latitude, correcting for time of day.

Case	Lat	Solar Flux [W/m2]	Hours post lunar sunrise	'Time' of lunar day	Equivalent Sink	Chamber Temp	Test Duration [hours]
Hot	84S	1414	212	Early afternoon	6°C	40°C	8+1
Cold	84S	1323	330	Late evening	-80°C	-120°C	8+1
PSR	84S	0	576	Midnight	-203°C	-190°C	2+1

Table 1: Overview of Environental Cases for TVAC Testing.

To determine hot environments, the model of the camera was placed in a full sun environment, one meter above the lunar surface, at the hottest part of the day. For cold environments, a semi shaded case during late evening was assumed. It is not currently known what the earliest/latest time of day Artemis III will experience, so an assumption of +/- 125 hours (~5 days) from lunar noon was used. The PSR case assumed no solar flux, a minimum regolith temperature, and a shorter duration for transient testing. Due to the large number of unknowns, a substantial amount of margin was added to these environmental temperatures. The TVAC chambers utilized in this testing attain cooling using LN2 in shrouds, limiting the minimum temperature attainable to roughly -190°C. This only affects the PSR case and does not allow for margin. Verification was done with analysis instead of testing for this case.

In order to measure the thermal performance of the cameras while in VAC/TVAC chambers, thermocouples (TCs) were adhered to external and internal components using Stycast. Additionally, internal temperatures of the storage card, image sensor, and an RTD on the main board was read while the LCD on the camera was on. These temperatures were logged and used to correlate a TD model of the camera, as well as to ensure that hardware did not exceed touch temperatures during operation. Chamber temperatures were recorded as well to provide boundary conditions.

An operational cycle was created early in the project to simulate the heat load generated by the camera. An Arduino controller was used to control the camera, wired through a passthrough in the vacuum chambers. The operational cycle can be broken into an 'active' state and a 'passive' state. The active state consisted of burst photography and panorama captures, while the passive segment allowed the camera to enter a standby mode. Once the chamber reached the desired temperature, the operational cycle was started with an active segment. Each segment lasted 60 minutes and was repeated as necessary to reach the desired test duration. In the event of a failure of the camera to operate, the time of test and causes of failure were noted, the camera given time to cooldown or heat up, and segments restarted. A table breaking down the operational cycle is below (Table 2) as well as a plot showing the expected thermal response to the use load (Figure 4).

Timestamp (s)	Operation(s)
0 – 30	- Power on/awake
30 – 90	- Panoramic shot - 10 x 3 shot burst - Pause
90 – 150	- 3 x 3 frame burst - Pause
150 – 270	- Powered off

Table 2: Overview of Operational Cycle for TVAC Tests.

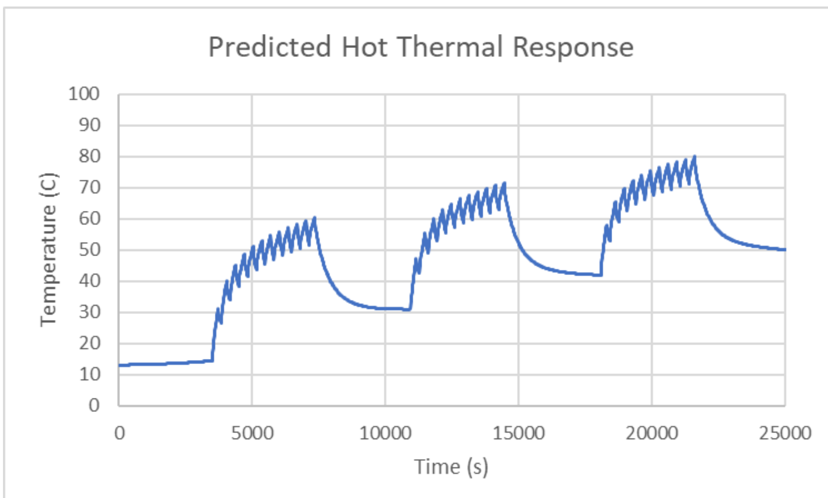

Figure 4: Predicted Thermal Response to HULC Operation Cycles.

RESULTS

The results of three main tests will be covered. More tests were run to help downselect hardware, compare changes in firmware, and provide data for model correlation. Due to the proprietary nature of the hardware being studied in this program, limited details may be provided.

The first test was to validate that the camera was capable of operating in an IVA environment. The IVA timeline included 30 minutes of continuous video recording at a high sampling rate, high resolution, and high frame rate. To better understand the effects of resolution and frame rate on thermal performance, those variables were altered for the three runs. Temperatures of the image sensor, main board RTD, and storage card are shown below in Figure 5.

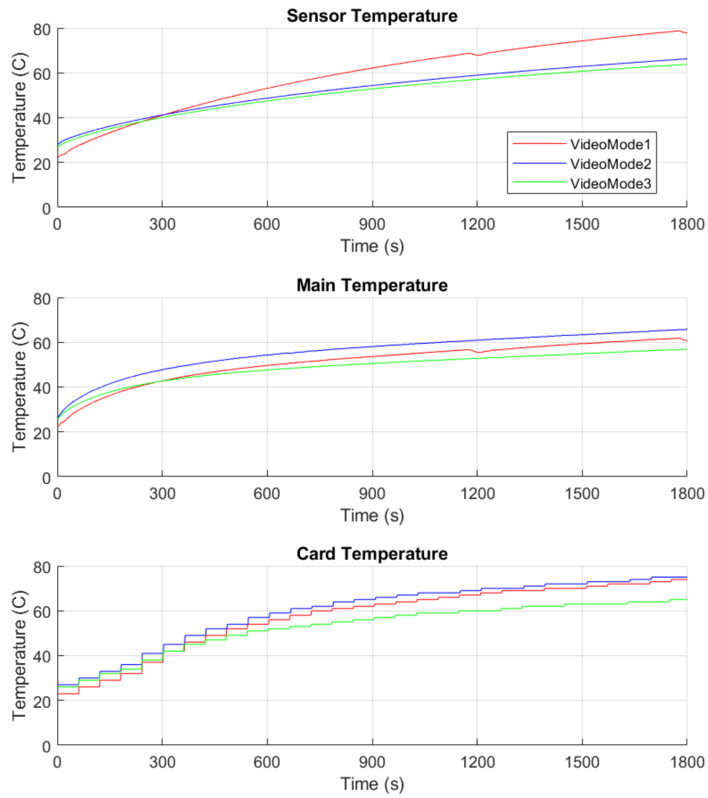

Figure 5: Internal Temperatures of the HULC During Video Tests.

The second and third test were held in a vacuum chamber capable of heating and cooling a shroud to induce an environment on the camera and TPS hardware. The first of these tests subjected the camera system to Hot, Cold, and PSR environments with simulated use on the camera. The second TVAC test kept the camera in a standby state to verify survival in determined environments. Plots of these tests are shown below. It is noted that for the Hot Operational test (plot 4 of 6), the camera reached an overtemperature limit and shutdown, causing the test to be suspended before the scheduled 9 hour run. A spike in the chamber temperature can be seen during the Cold Operational test. This was due to a faulty valve with the chamber setup and was deemed to not invalidate the test.

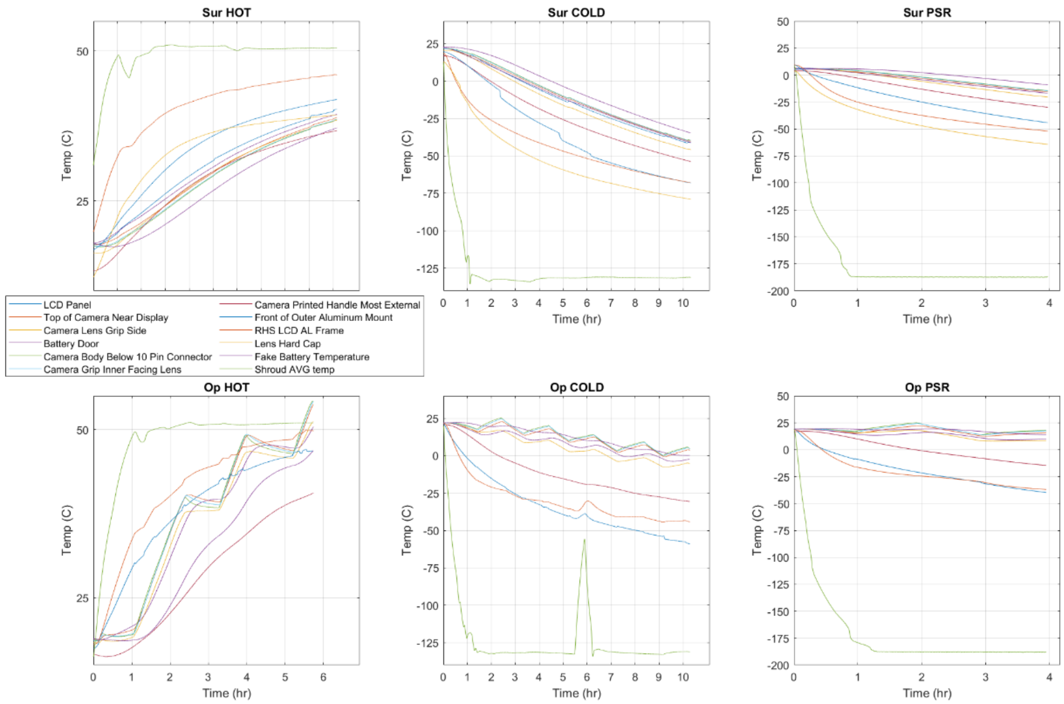

Figure 6: Thermal Results from TVAC Testing of the HULC.

DISCUSSION AND MODEL

The results from both IVA and EVA testing indicated that the camera and associated TPS was able to maintain functionality across extreme temperatures. The camera sustained operation in temperatures as low as -187°C and as high as 50°C. The camera performed an over-temperature shutdown during the operational test in the hot environment, but due to the amount of margin and the fact that the camera survived for the required amount of time, it is believed that the TPS is sufficient for hot environments.

Data from these tests and other TVAC tests were used to correlate a Thermal Desktop model. This can be used for future cases when the landing environment is more realized, allowing for a more realistic temperature prediction. Additionally, the Thermal Desktop model allows for custom power profiles to be applied to components within the camera. This ability ensures that accurate internal temperatures can be predicted if the use case of the camera changes or is updated. A plot of the model predictions is shown in Figure 7, along with the matching test data.

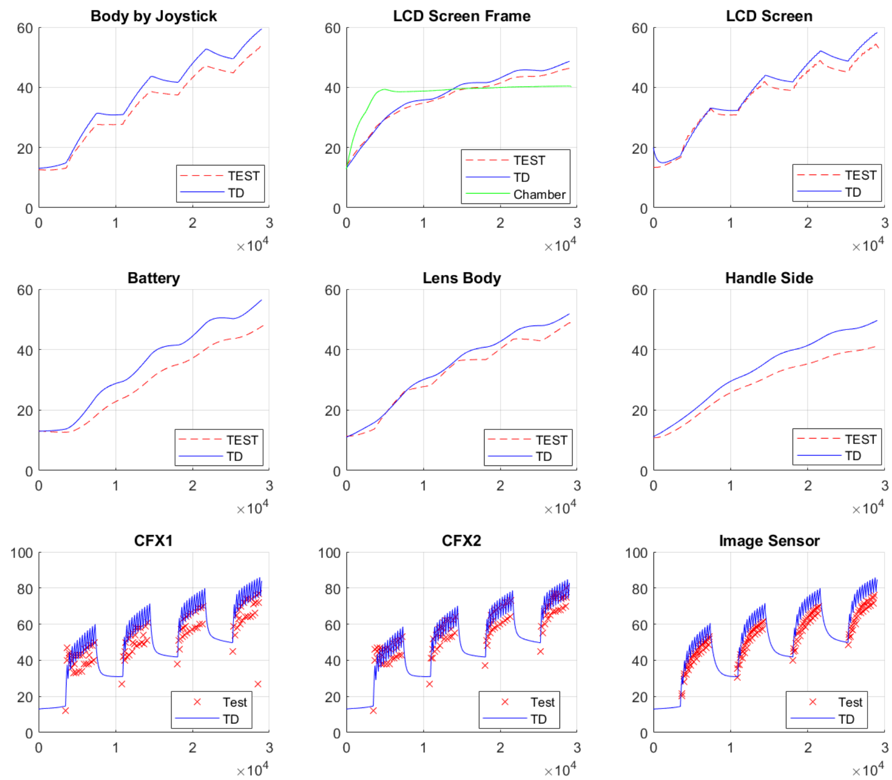

Figure 7: Comparison of the HULC Compared to Thermal Desktop Model Predictions.

The findings from these tests demonstrated the effectiveness of the designed TPS in protecting the camera under simulated lunar environments. The ability of the camera to operate in a wide temperature range supports its use in future lunar missions. More testing is necessary to better identify the reduced operational time under high temperature environments, and a better understanding of the anticipated lunar environment will help to elucidate performance issues.

CONCLUSION

In conclusion, the thermal vacuum testing of the modified COTS camera has validated its capability to function in the harsh conditions expected on the lunar surface. The TPS proved to be effective, although improvements may be necessary to extend the operational duration in higher temperature environments, or during heavy use cases. These findings contribute to the ongoing efforts to develop reliable, cost-effective technologies for space exploration. The modified COTS camera presents a promising option for future lunar missions.

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