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THERMAL DEVELOPMENT OF A COMMERCIAL OFF THE SHELF (COTS) CAMERA FOR EXPLORATION UPPER STAGE (EUS)

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ABSTRACT

NASA's Flight Imagery Launch Monitoring Real-time System (FILMRS) cameras were originally developed for the Space Launch System (SLS) Core Stage. These Commercial Off the Shelf (COTS) cameras have been redesigned and reduced by an order of magnitude in size for the Exploration Upper Stage (EUS). The change in thermal environment has led to the application of various passive thermal control methods and the addition of a heater option. This paper will give a summary of the design and development test effort associated with adapting the COTS camera for the demands of the space environment and associated thermal mitigations applied as the project prepares to complete the design. The application of this camera for other space systems is discussed.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

COTS	Commercial Off the Shelf
EFILMRS	EUS Flight Imagery Launch Monitoring Real-time System
ELCA	EFILMRS Lighted Camera Assembly
EUS	Exploration Upper Stage
FEP	Fluorinated Ethylene Propylene
FILMRS	Flight Imagery Launch Monitoring Real-time System
LEO	Low Earth Orbit
SLS	Space Launch System
TD	Thermal Desktop
TLI	Translunar Injection

INTRODUCTION

Use of Commercial Off the Shelf (COTS) cameras for imaging in space reduces cost, development time, size and volume, but COTS units require modifications to perform adequately in the vacuum and thermal environments of space. The Flight Imagery Launch Monitoring Real-time System (FILMRS) Lighted Camera Assembly (ELCA) from the Space Launch System (SLS) Core Stage has been redesigned to survive space environments. As such, this design serves as a starting point for thermal design of other space use cameras.

THERMAL CHALLENGES FOR COTS IN SPACE

The Exploration Upper Stage (EUS) EFILMRS objective was to convert the ELCA for extended use in space while reducing size, volume and power requirements. This required a complete redesign of the system from the original design for a short 20-minute operational life in space. Figure 1 shows the size, weight and power difference between the original FILMRS design and the revised EFILMRS design. The ELCA weight and volume were reduced to 1/10th of the original while power was reduced to 1/3rd.

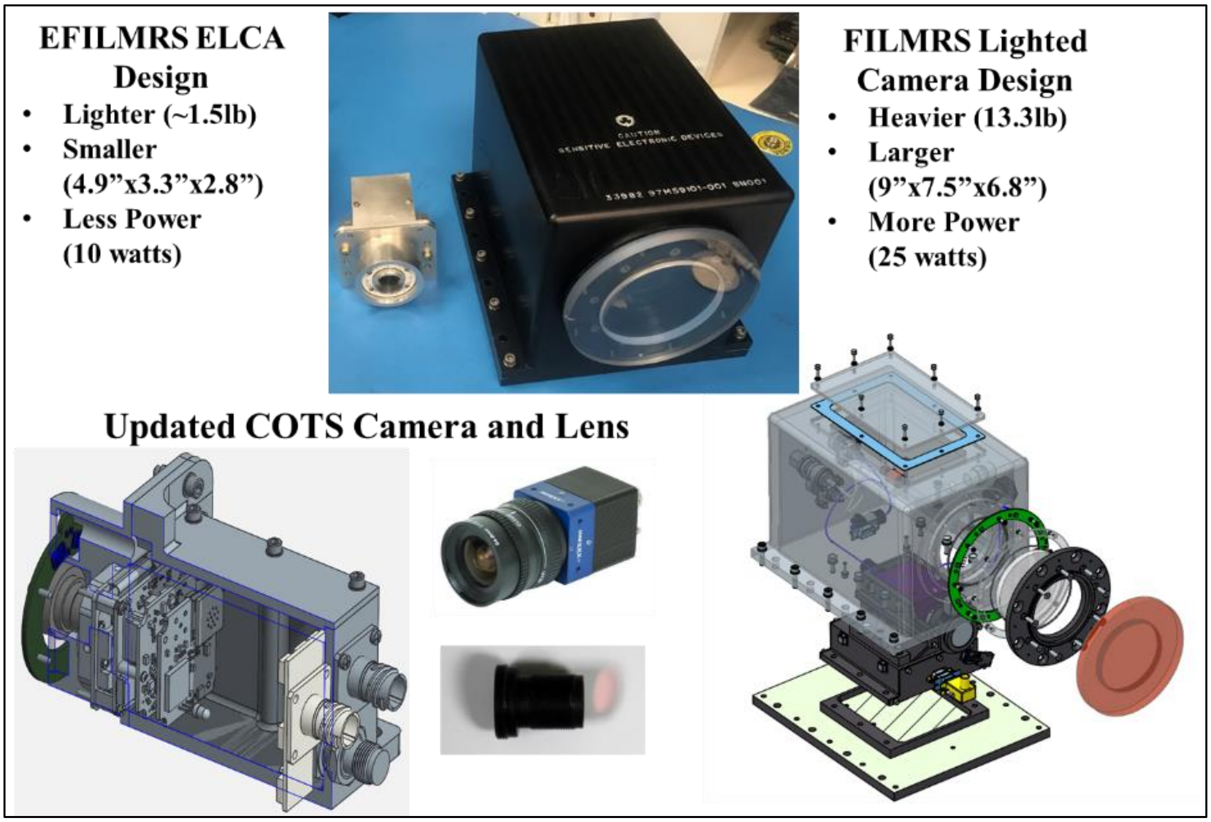


Figure 1. Comparison of FILMRS SLS Core Stage design to the EFILMRS EUS design.

Extended EUS Space operation requires up to eight hours of vacuum operations including exposure to Van Allen belt radiation with non-rad-hardened components, high vibrational loads, and temperature extremes. Typically, COTS components underperform in space thermal environments as compared to space built components since conductive pathways were not sufficient to prevent heat buildup. As such, the use of passive thermal mitigations to increase the conductive pathways were the key to providing enhance operational life in space while keeping the size and mass small. In extreme cold environments, the EFILMRS camera power usage was so low that self-heating during cold operations was limited.

The EFILMRS cameras were required for three different locations: an equipment shelf, an external fairing enclosure and on a Payload Adapter (PLA). Passive thermal mitigations were only sufficient for the cameras located in the external fairing and equipment shelf locations. PLA camera exposure could include solar loads and deep space views over much of the eight-hour mission duration including Low Earth Orbit (LEO) and Translunar Injection (TLI) phases. As such, these cameras required additional environmental mitigations.

The imaging hardware has a safety designation to “do no harm” to the vehicle in the event of a failure or, in other words, an imaging system failure would not propagate any safety issues for the vehicle. This designation implies that cameras were not required to be fault tolerant. Management evaluation of risk associated with various potential failures was on a case-by-case basis considering the cost, schedule and performance impacts. This methodology means the thermal design was not required to have the same degree of margin as typical for space vehicles components. Thermal mitigations were incorporated with an overall goal to have sufficient thermal margin to minimize system risk of failure.

Typically, COTS hardware cannot withstand the temperature extremes of hardware built for space applications. Instead of developing a thermal design based on environments, the approach taken with the COTS hardware was to provide some thermal mitigation, define the COTS hardware limits, compare limits to flight predictions, and iterate on this process to develop a thermal design. First, simple thermal passive mitigations, such as chassis material and exterior optical properties, were selected for the design to minimize temperatures extremes. Next, the camera temperature limits were determined by component level thermal development testing. After that, the test limits were compared to flight performance predictions to define the system margin. Finally, the system margin was evaluated to determine if it was sufficient. For the “do no harm” safety designation, the definition of “sufficient margin” was determined by management review based a recommendation from the thermal analyst. If the system margin was insufficient, then additional design mitigations would be evaluated using the same process. These could be at either the COTS or integrated design level and selection depended on the relative design impact of these mitigations.

ELCA THERMAL DESIGN

Thermal design for the ELCA has included COTS camera testing and application of initial thermal mitigation in the form of encapsulation and housing design. Early testing of the COTS cameras included acceptance testing of the COTS camera on receipt from vendor and after encapsulation. Early testing showed the encapsulation performance in vacuum and thermal chamber (in atmosphere) testing. This provided data to develop COTS thermal analysis models. The evaluated thermal design used both steady state and transient analysis of the ELCA using PDR level integrated environments. ELCA development unit level thermal testing to define the component temperature limits is upcoming in fall. As such, the design is still able to adapt.

Application of this COTS approach to the ELCA has resulted in addition of several passive thermal mitigations. All cameras include encapsulation material in the camera housing, building the housing out of aluminum for conductivity, and black anodizing on the housing exterior. Additional mitigations for the extreme PLA environment include addition of an exterior optical coating, mounting location isolation, and heaters.

From thermal chamber test data, a thermal transient model of the encapsulated COTS camera was developed and correlated. Early steady state analysis showed concerns with meeting environmental temperature extremes. Given the transient variation in the environment, a transient analysis was developed for a more representative response to the environment.

Encapsulation

The encapsulation material, Conathane EN-11[i] [1], has a history of use on NASA probe projects. For reference, this material provides a room temperature conductance of 0.2 W/m/°C which is ten times more conductive than the air. Additional benefits include holding the internal components in place and mitigating high g-vibrational loads. The epoxy encapsulates the COTS camera cards within the camera housing as shown in Figure 2.

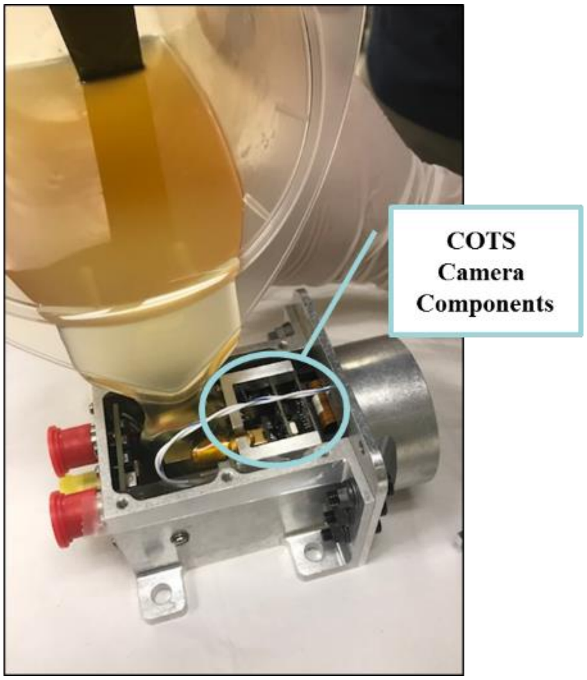


Figure 2. Encapsulation of for the ELCA.

Testing the encapsulation process and effectiveness in vacuum was part of the early design development process. Figure 3 illustrates the encapsulation process used for the test cameras. Preparation of the COTS camera included dissemble and taping the body exterior to prevent leaks. First, the encapsulation process began with measured amounts of parts A and B, mixed thoroughly. Second, outgassing of the liquid epoxy was performed in a vacuum bell jar at about 30 Torr. Third, the honey like epoxy was poured into the camera housing until full. Note the thin wires protruding from the top of the camera were thermocouples located near each of the three boards, suspended within the epoxy. Fourth, the unit was bake out at 60°C for 24 hours to cure the epoxy. Visual evaluation of the material, as cured, showed no air bubbles or air pockets. After encapsulation, the camera was reassembled and tested. Vacuum testing proved the camera could operate in a 5.8x10-7 Torr pressure with good image quality. Unfortunately, the chamber used was unable to control environment and temperature results were all transient.

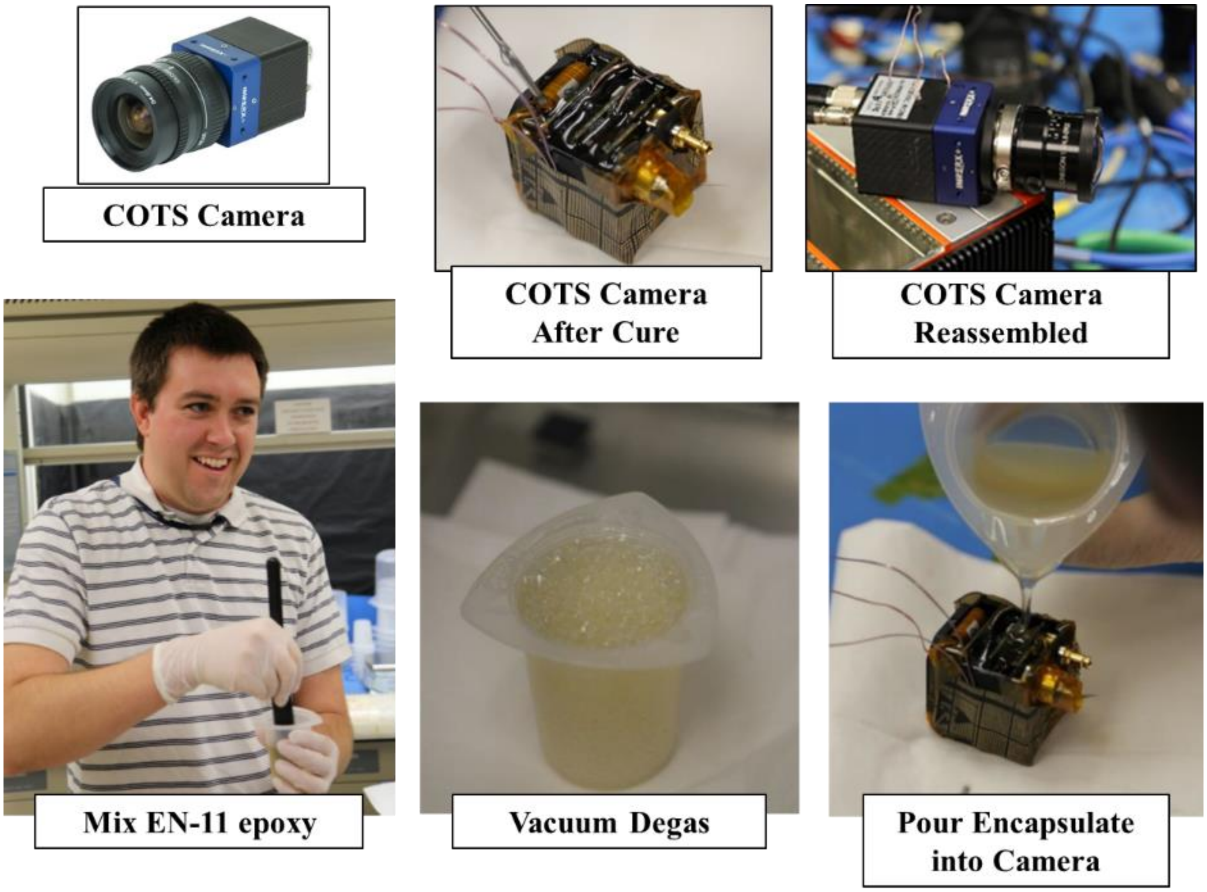


Figure 3. Encapsulation process for the COTS camera test.

ELCA Thermal Tests

Both thermal chamber tests in vacuum and atmosphere were performed. The vacuum chamber test showed transient performance in vacuum, but the chamber was not able to control the environment to provide a vacuum steady state response. Thermal cycle testing was with three encapsulated cameras in a thermal chamber (in atmosphere). The case matrix included one temperature cycle at +75°C to -20°C and two cycles at +85°C to -30°C, the vendor defined limits. Note the vendor limits were for the chassis of the camera, not internal components. The test goal was to characterize the conduction path from internal cards to the camera housing through the EN-11. This conduction path would be the same regardless of the presence of vacuum.

Test instrumentation included three type T thermocouples internal to the camera, located within the encapsulation material suspended between each of the cards, one each on the top and sides of each unit, and one on the mounting plate near each camera. Figure 4 provides an overview of the test set up in the thermal chamber.

For each temperature case, the unit was soaked at the environment temperature before start up to ensure all components were at a uniform temperature. Operation started after the soak to provide a transient heating profile for model correlation. Steady state operation was define as a temperature change of no more than 2Δ°C in any camera TC held over a 15-minute period. During testing, it was found that encapsulated TC2 was damaged and some of the side camera TCs came loose as the test progressed. These data points were removed from further analysis. Reduced test data, Table 1, shows steady state results averaged over all remaining sensors for each environment temperature.

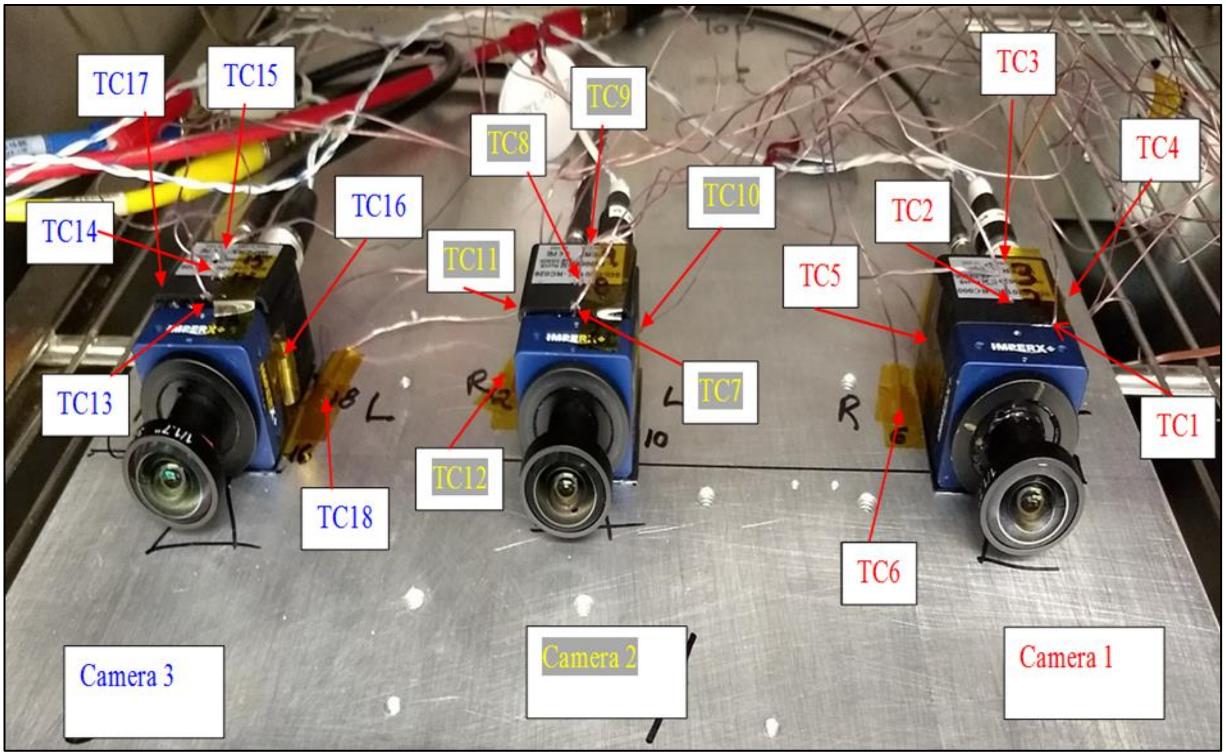


Figure 4. Thermal Chamber Test Set-Up.

Table 1. Thermal Chamber Test Result Summary

Averaged TC Reading	Hot Steady State at 75°C	Hot Steady State at 85°C	Cold Steady State at -20°C	Cold Steady State at -30°C
Chamber	76.6	86.6	-19.9	-30.8
Camera Mounting Plate	77.6	87.7	-19.4	-29.5
Internal Camera Front	88.0	98.6	-7.7	-17.2
Internal Camera Middle	91.8	102.6	-4.4	-13.5
Internal Camera Back	92.0	102.7	-5.2	-14.7
External Camera Left	78.8	90.0	-17.7	-26.6
External Camera Right	78.4	88.6	-18.2	-27.7

Thermal Model Development

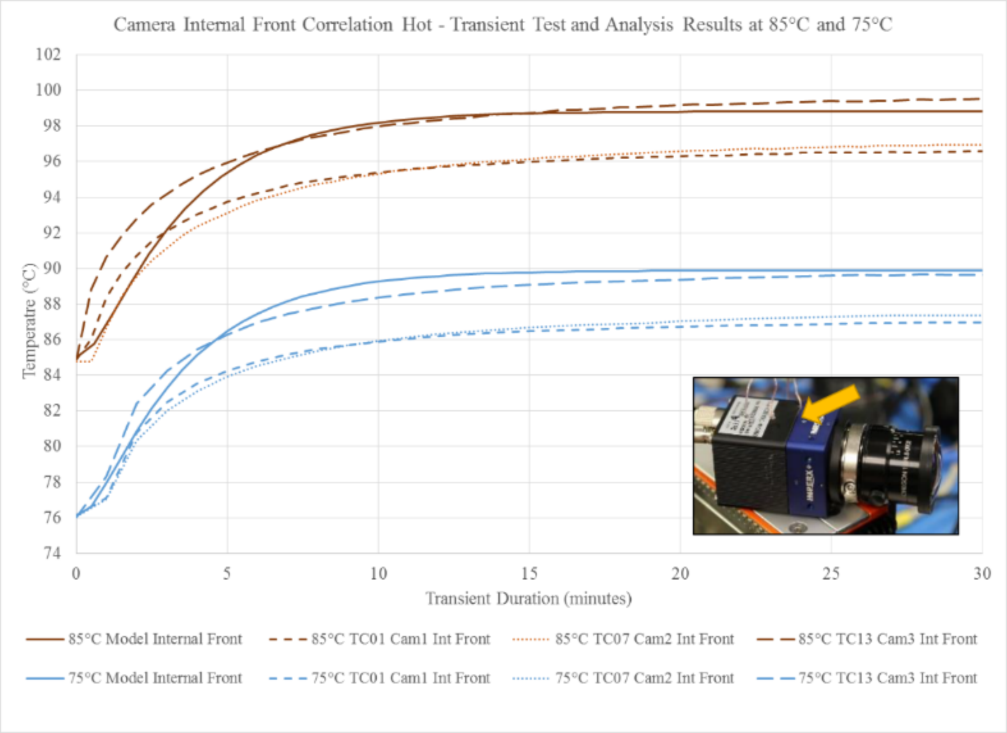
This COTS camera test data provided a basis for development of the ELCA system transient thermal model. First, a model of the test configuration was developed within Thermal Desktop[ii] (TD) [2]. Second, the test data was used to correlate to the COTS camera model. Finally, the COTS thermal model was adapted to develop a system level ELCA thermal model. The objective of this model effort was to predict flight environment extremes and evaluate thermal mitigation options as needed.

COTS Camera Model Correlation

The TD model of the COTS camera was a simple representation including the PCB cards, EN-11 layers and housing, shown in Figure 5. Component geometry was gathered from CAD information and physical cameras. The PCB cards were simple surfaces without components, so increased mass and applied power were used to simulate components on the cards. Once materials were defined for all components the model mass was compared to actual mass to define a density factor within TD. The camera power was disturbed between the PCB cards as needed to match test results.

The environmental conditions included setting the mounting temperature, radiation sink temperature and total heat load from test data. Comparison of predictions to the transient test data for each of the four environments resulted in adjustment of power and contact parameters. The parameters adjusted include the following:

- Power distribution between PCB cards
- Encapsulation contact factor between PCB card layers
- Encapsulation contact factor to the housing wall
- Natural convection factor on the exterior of the camera
- Contact factor between the front housing and sensor



For hot and cold environments, Figure 6 and Figure 7, respectively, show the correlated model predictions and test data transient for the front card TC where solid lines represent model predictions. This shows the model tends to slightly over predicts temperatures. Table 2 shows a comparison of test data and model predictions at 6 minutes, 9 minutes, 25 minutes and steady state where the worst-case delta for each reading is in red. The overall worst-case difference was 3.9 Δ°C early in the 75°C environment transient.

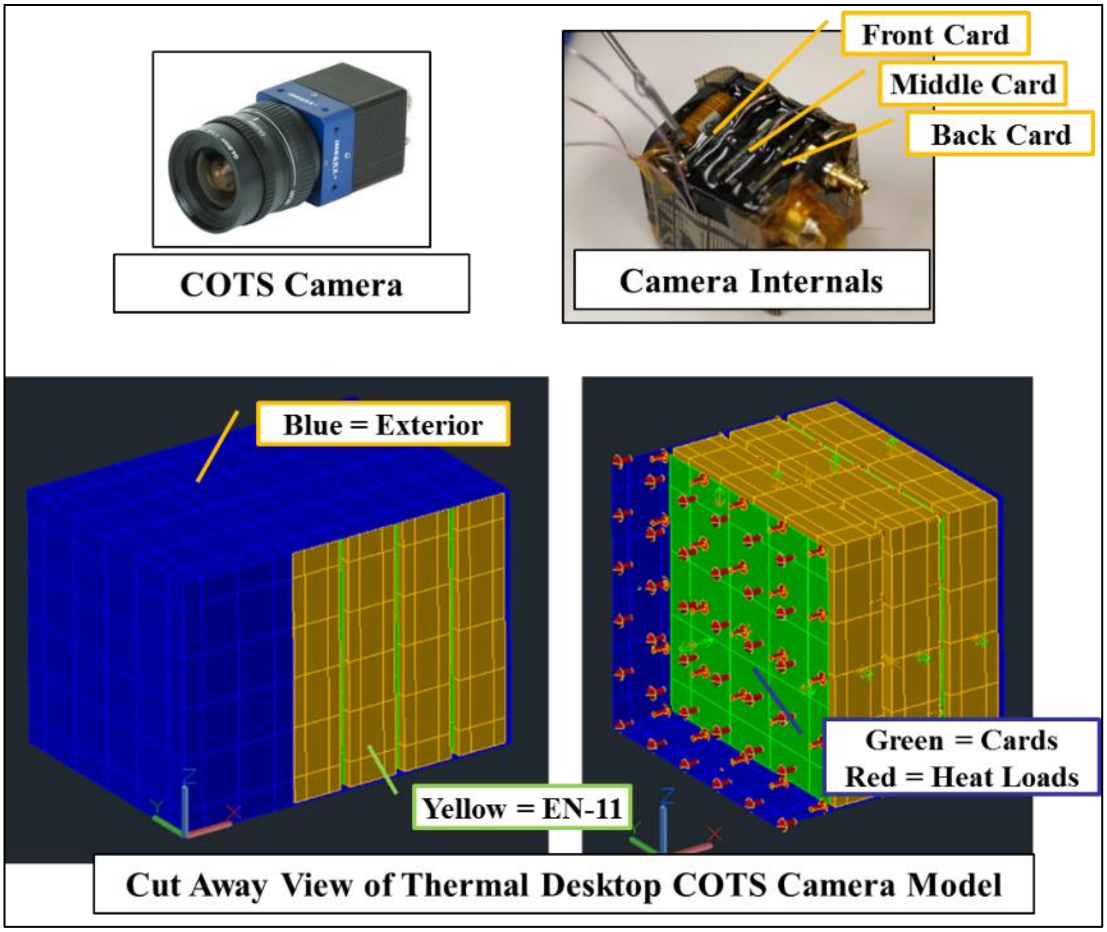


Figure 5. COTS Camera Thermal Desktop Model.

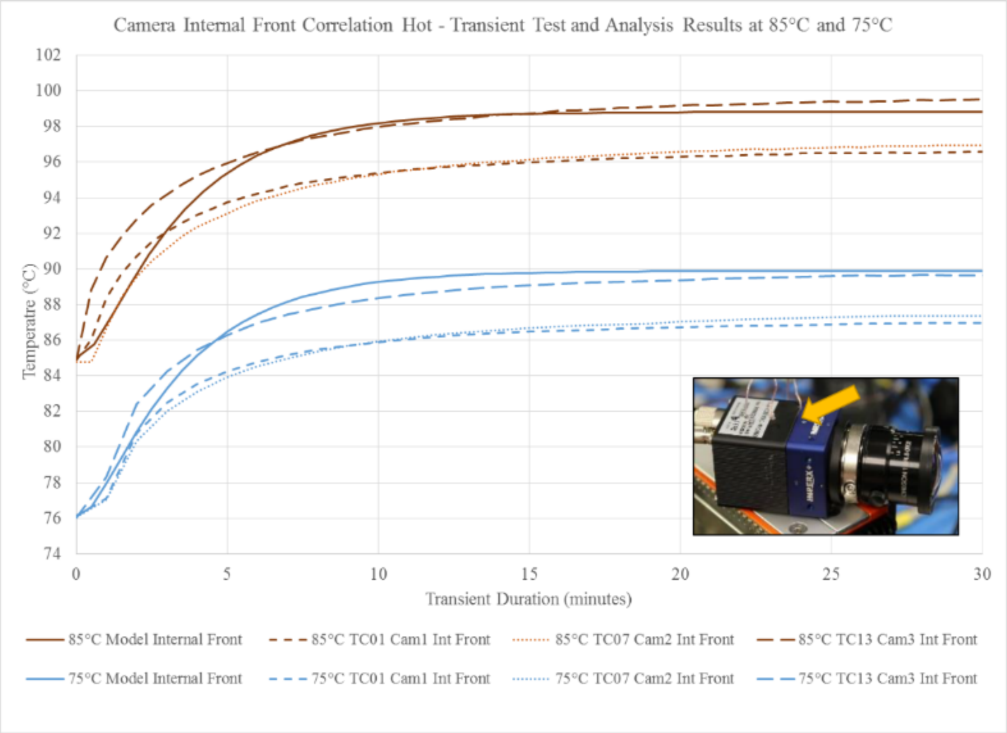


Figure 6. Hot Case Internal Front Camera Predictions Compared to Transient Test Data.

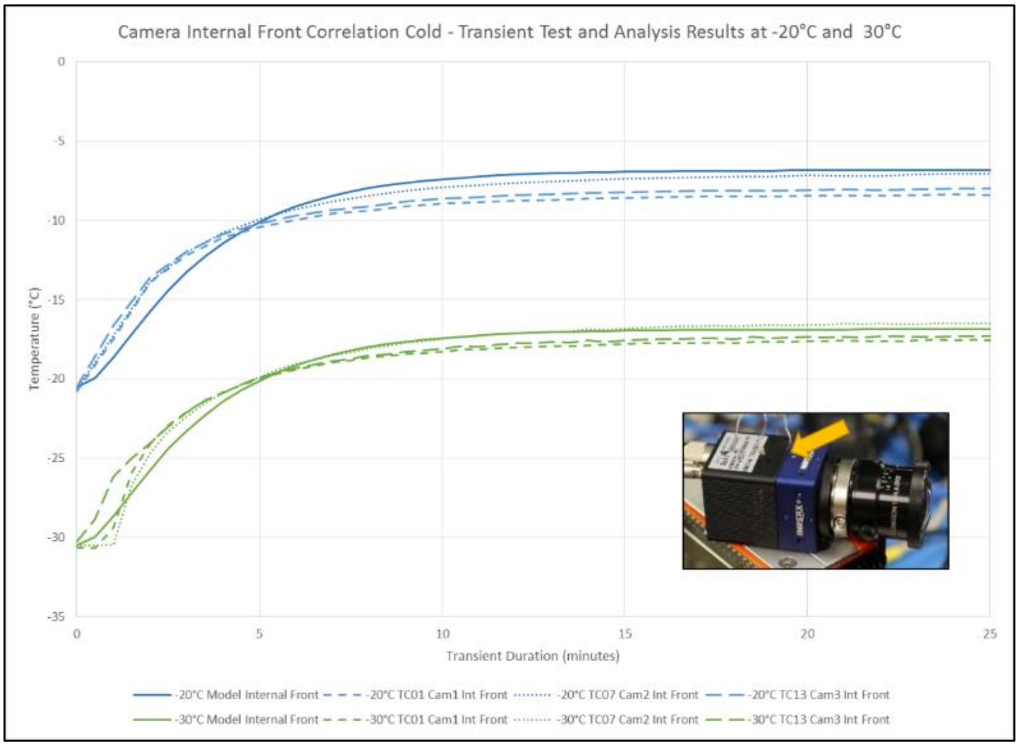


Figure 7. Cold Case Internal Front Camera Predictions Compared to Transient Test Data.

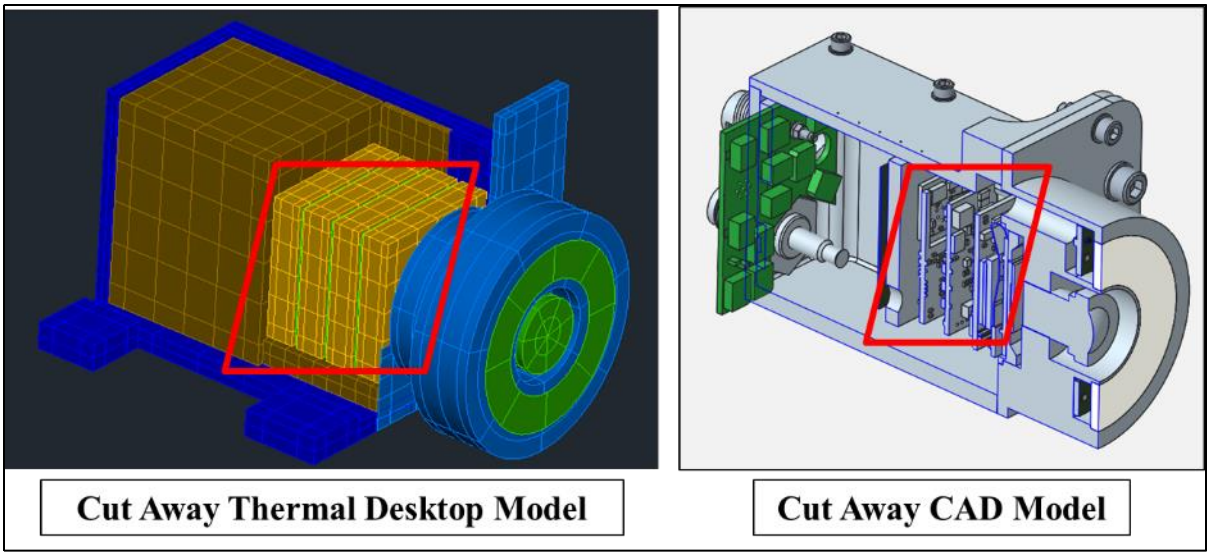
Table 2. Averaged Test Data and Model Correlation Comparison

Time	Chamber	Mount	Internal Front			Internal Middle			Internal Back			External Side		
			Model	Test	Delta	Model	Test	Delta	Model	Test	Delta	Model	Test	Delta
6 min	-19.9	-19.4	-9.1	-9.7	0.5	-4.3	-6.5	2.2	-5.9	-7.1	1.2	-17.2	-17.9	0.8
9 min			-7.6	-8.8	1.2	-2.6	-4.9	2.3	-4.3	-4.9	0.6	-16.7	-17.5	0.8
25 min			-6.9	-8.0	1.2	-1.7	-3.5	1.8	-3.4	-3.0	-0.4	-16.5	-16.9	0.4
Steady			-6.8	-7.7	0.9	-1.7	-4.4	2.7	-3.4	-5.2	1.7	-16.5	-16.5	0.0
6 min	76.6	77.6	87.4	86.9	0.5	92.2	88.3	**3.9**	90.7	88.7	**2.0**	79.5	78.6	0.9
9 min			89.0	88.1	0.9	94.0	90.1	**3.9**	92.3	91.2	1.2	80.0	79.1	0.8
25 min			89.9	89.6	0.3	95.0	92.2	2.8	93.3	93.7	-0.5	80.2	79.9	0.4
Steady			89.9	88.0	**1.9**	95.0	91.8	3.2	93.3	92.0	1.3	80.2	80.1	0.2
6 min	-29.7	-29.0	-19.1	-19.3	0.2	-14.3	-16.5	2.1	-15.9	-17.2	1.3	-27.2	-26.7	-0.4
9 min			-17.7	-18.3	0.6	-12.6	-14.6	1.9	-14.3	-14.8	0.5	-26.8	-26.0	-0.8
25 min			-16.9	-17.3	0.4	-11.7	-13.0	1.3	-13.5	-12.7	-0.8	-26.5	-25.5	-1.0
Steady			-16.9	-17.1	0.2	-11.7	-13.7	2.0	-13.5	-14.5	1.1	-26.5	-25.2	**-1.4**
6 min	85.7	86.7	96.4	96.5	-0.2	101.1	97.6	3.6	99.6	97.8	1.8	88.4	88.0	0.4
9 min			97.9	97.7	0.2	102.9	99.5	3.4	101.3	100.5	0.8	88.9	88.7	0.2
25 min			98.8	99.4	-0.6	103.9	101.8	2.1	102.2	103.5	-1.3	89.2	89.8	-0.6
Steady			98.8	97.7	1.1	103.9	101.7	2.2	102.2	101.8	0.4	89.2	89.8	-0.6

ELCA Model Development

All ELCA locations contain the same COTS camera, but the lens can differ. ELCA model was built around the encapsulated core of the COTS camera model, i.e. the camera cards and encapsulation layers. The CAD model of ELCA aluminum housing provided the basis for a TD geometry model. Once materials were defined for all components the model mass was compared to actual mass to define a density factor within TD.

The lightweight framework holding the camera cards was omitted in this analysis because it was sandwiched between EN-11 layers, so EN-11 limits the heat transfer out of the camera. A solid represents the lens and lighted ring PCB. The lens body material was assumed to be solid aluminum, so conduction would result in the worst-case temperatures extremes internal to the camera. Encapsulated areas within the housing beyond the COTS camera area were TD solids. Contactors were added to simulate the encapsulate conduction to the aluminum housing. Comparison of the CAD and TD model geometry is in Figure 8. The lighted ring load was applied uniformly to the LED PCB and the camera loads were distributed as determined from test correlation.


Cut Away Thermal Desktop Model

Cut Away CAD Model

Figure 8. ELCA Thermal Model Compared to CAD Model.

PLA Design Mitigations

The PLA ELCA required several passive thermal mitigations to minimize temperature extremes. Operation in cold environments below -20°C resulted in intermittent failure of the COTS camera, and temperatures below -30°C caused failure of some COTS camera components. The PLA ELCA exposure was well below these ELCAcold limits during flight. Passive thermal mitigations were unable to counteract these cold temperatures, so heaters were required to keep these ELCAs within operating limits.

The heater system used up to 28W based on design limitations for the system. The camera heater system consisted of four polyimide thermofoil heaters, 1 inch by 1 inch, with a 25W/inch density. Heaters were attached to two COTS PCB cards before encapsulation with EN-11. The heaters were linked two in series and two in parallel for one fault tolerance to a single heater failure. The heater sensor was located behind the back PCB card. A temperature resistor in the circuit opens to shut down the heaters if temperatures rises above 128°C to prevent heater runaway.

To optimize the heater effectiveness, the ELCA was isolated from the mounting location. The isolation material size was 0.25 inch, G-10 fiberglass laminate. To minimize heat input during solar viewing environments, the exterior of the ELCA was coated with sliverized FEP (Fluorinated Ethylene Propylene) tape to minimize solar heat gain and maximize IR heat rejection capability. The tape was 10-mil thick second surface sliver coated FEP tape with acrylic 966 adhesive [iii][3] where an overcoat of Inconel was provided on the silver to prevent oxidization. It provides a low absorptivity of 0.10 and high emissivity of 0.85.

Preliminary analysis of the heater operation was performed for a PLA camera in a cold environment. The analysis assumes isolation of the ELCA and a low hysteresis band of 2Δ°C and a desired temperature of no less than -15°C. Preliminary analysis of the heater operation for a PLA camera in a cold environmentis in Figure 9. The housing stayed above the cold limit while the internal PCB cards were much warmer.

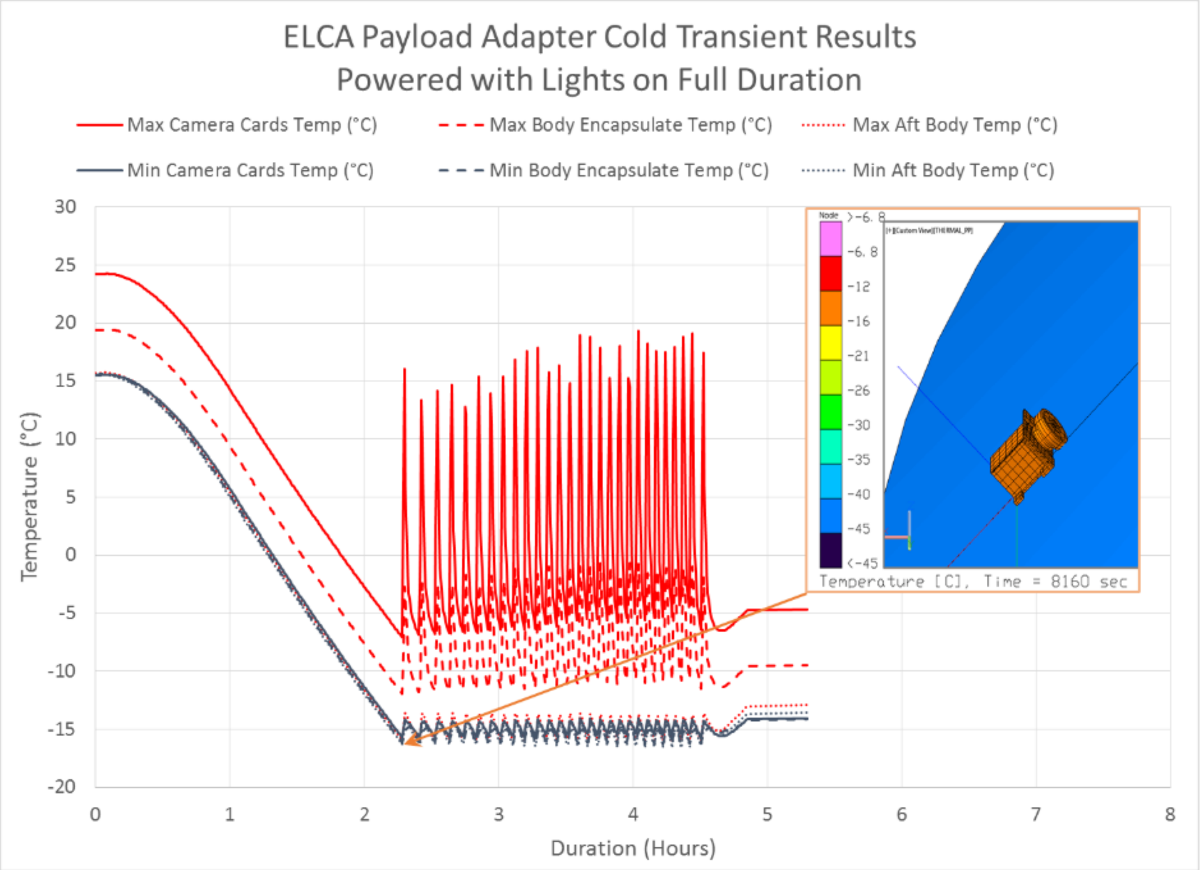


Figure 9. ELCA with Heater Analysis Predictions.

CONCLUSIONS

Thermal design with COTS requires concurrent thermal development testing to characterize performance and define operational limits. COTS components were not designed for the extremes of a space environment and analysis was limited to information provided by the vendor. By testing development units and building correlated models, a better understanding of the performance limitations was gained while providing modeling data to evaluate mitigations. In the case of a lightweight passively controlled camera, exposed to space, transient thermal models were needed to simulate the system response.

Mitigations were key to assuring COTS components were within limits. Use of encapsulation material EN-11 provided a mitigation for missing air conduction due to the vacuum environment. The thermal design of the enclosure improved thermal performance significantly by including thermal mitigations, such as an aluminum housing, defined contact at the mounting interface (either isolation or direct contact), and optical properties, used to moderate heat rejection. Extended exposure to cold environments required an active mitigation of heaters.

Forward work

EFILMRS ECLAs are in the design process with thermal development testing of the integrated ELCA unit scheduled for early fall 2019. The testing goal is to obtain ELCA component temperature limits and gather thermal balance data for model correlation. Once data is gathered, it will be applied to the thermal model developed to date for correlation of a transient model.

Other applications

Once the design of the ELCA is complete it can be applied to other space projects needing cameras. This is already in process on for Low-Earth Orbital Flight Test on Inflatable Decelerator (LOFTID). LOFTID is a demonstration flight of an advance inflatable aeroshell. The EFILMRS ELCA will be used to provide visual spectrum data for comparison to IR data collected.

ACKNOWLEDGEMENTS

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CONTACT

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[i] Cytec Industries, Conathane EN-11, www.cytec.com/conap

[ii] T. Panczak, S. Ring, M. Welch, D. Johnson, B. Cullimore, D. Bell. C & R Technologies (R) Thermal Desktop (R) User's Manual, A CAD Based System for Thermal Analysis and Design, Version 6.0.

[iii] Sheldahl, RedBook Rev C, Second Surface Silver Coated FEP Tape with Acrylic 3M™ 966 Adhesive, page 62, www.sheldahl.com