Characterization and Analysis for Flying COTS Electronics On-Orbit

Jason D. Niederhauser, Jonathan T. Black, Carl R. Hartsfield
Air Force Institute of Technology
2950 Hobson Way, WPAFB, OH 45433; (937)255-3636
jason.niederhauser@us.af.mil, jblack@afit.edu

ABSTRACT
As part of the Air Force Institute of Technology's efforts to develop and fly a novel imaging chromotomographic spectrometer payload in space, this work accomplished an investigation of hermetic enclosures to house commercial, off-the-shelf (COTS) components. Rationale for expending research efforts herein is attributable to enabling use of electronics which may not be available in a space-qualified form for years and to reduce cost/schedule constraints. Thermal modeling was validated through performance of a design, analysis and test campaign.

INTRODUCTION
The Air Force Institute of Technology is currently developing and planning to fly a novel multifunctional imaging chromotomographic (CT) spectrometer payload in space. This spaceflight experiment will demonstrate the utility of this type of sensor design to perform multiple remote sensing missions in orbit. Current Earth Observation (EO) payloads typically require a point design (or a few point designs) in which spectral, spatial, and temporal resolution are set prior to launch and either cannot be altered on orbit or can only be changed within a small range. Example missions include missile launch detection, static-scene hyperspectral collection, and rapid transient event characterization. The high launch cost of placing payloads in orbit necessitates that each sensor is optimized for its particular mission, and therefore may not be effective in performing other tasks. The multifunctional imaging CT spectrometer flight experiment (CTEx) will demonstrate the flexible potential of these sensors to perform multiple remote sensing missions in orbit. The instrument is very simple relative to other spectrometers, consisting of a standard optical telescope, a rotating dual or direct vision prism inserted along the optical path, and a camera. During the measurement of successive video frames, the dispersion axis is rotated, causing the image of the spectral features to trace out circles with wavelength dependent radii. This rotation has the effect of multiplexing the color information of the image over the array, which, otherwise, is operating as a broadband polychromatic sensor. Tomographic computational methods similar to the limited-angle tomography used in medicine are used to reconstruct the scene. This technology has been under development for several years in various research programs, but has yet to be successfully adapted to space. The overall CTEx flight program will design, test, and build a prototype of an experimental or proof-of-concept CT spectrometer space payload. The functionality of the sensor will be proven by collecting data from and characterizing natural events such as forest fires and potential targets of opportunity such as planned detonation events. These large combustion events will demonstrate the CT science from space. The end result of this research effort will be a designed, prototyped, and tested multifunctional CT payload suitable for launch as part of a future sponsored effort.

One important yet not as overt mission requirement for CTEx is to demonstrate new and innovative ways to develop and build the experimental payload in order to reduce cost and schedule (as this is a university project). To accomplish this objective, use of commercial, off-the-shelf (COTS) components and hermetic enclosures are employed throughout the design, including the camera, computer, telescope controllers and rotation stage. The benefit this provides to the CTEx mission is in opening the door to the use of aircraft-grade components and computers which may not be available in a space-qualified form for years. Specifically, this research effort related to the design, analysis, and characterization test campaign encompassing the space-based CTEx instrument computer unit (ICU). The intent is to fly COTS electronics in space with a goal of scaling the hermetic enclosure size to house motor actuator controllers in the CTEx Telescope Control Unit (TCU). This activity produced a validated mathematical thermal model supporting the trade-space refinement and operational planning aspects for the device.
DESIGN REQUIREMENTS

The design of the ICU had to meet several requirements, providing a baseline for this design development. These baseline requirements are listed below.

- Utilize commercial, off-the-shelf (COTS) electronics and mechanical hardware as much as possible
- Minimize mass to 10 kg, or less
- Ensure the fundamental frequency is above 50 Hertz in all axes
- Ensure the design will survive normal operations in a high vacuum/space environment
- Meet all regulatory requirements associated with H-II Transfer Vehicle (HTV), Expedite the Processing of Payloads to the Space Station (EXPRESS) Pallet Adapter (ExPA) and International Space Station
- Do not dissipate excess thermal loading to the ISS (or surrounding structure/devices)

Prior to assessing the mathematical model and computer-aided design work, a determination for the type of thermal loading on-board needed to be understood. Due to the fact that the PC/104 configuration is a relatively wide-spread form-factor in ruggedized military applications, utilization in the CTEx program as an avionics platform made practical sense from a design standpoint. Thus, a preliminary assessment pertains to the anticipated CTEx ICU PC/104 stack, which will likely include: CPU, solid-state drive, internal I/O (e.g., Ethernet, SATA, and/or RAID cards for high throughput data transfer to/from the high-speed camera), and external I/O (e.g., 1553 for communication with the ISS). As an option, a pressure/temperature card (for health monitoring) and universal power supply may also be integrated. From this notional CPU construct, we can expect a stack power usage of roughly 25 W (nominally). Thus, this power level is also factored into the design requirement trade-space as the design progresses. Next, we will explore the mathematical thermal model developed to assess this power input to the system.

THERMAL MODELING METHODOLOGY

As an initial characterization for the ICU thermal environment, a one-dimensional lumped-capacitance model was developed for early predictive purposes. This model, upon validation through testing, will be utilized to map the design trade-space. Figure 1 is the general control volume concept for this model development.

![Heat Transfer Control Volume Concept](image)

Figure 1: Heat Transfer Control Volume Concept

This control volume theory can be related to the first law of thermodynamics, Equation (1):

$$\dot{E}_{st} = \frac{dE_{st}}{dt} = \dot{E}_{in} + \dot{E}_{g} - \dot{E}_{out}$$

(1)

Where $\dot{E}_{st}$ is the energy stored within a control volume changing with time (W), $\dot{E}_{in}$ is input energy changing with time (W; e.g., albedo, Earth infrared, etc.), $\dot{E}_{g}$ is the rate of generated energy (W; e.g., PC/104 electrical input power, fan and other sources) and $\dot{E}_{out}$ is the rate of output energy (W). Moreover, Equation (6) is the conservation of energy, in that no additional energy will enter or leave the system unless an equal or opposite change is experienced elsewhere in the model.

More specifically, we now assess the particulars of our situation through breaking up the constituents of nominal, routine on-orbit operations. The ICU is initially viewed as an independent unit, passively cooled, and thermally isolated. From a simplistic perspective, the highest temperature found within the device will likely be that of the CPU. The cooling circuit will consist of using a fan to circulate a pure and dry gaseous-nitrogen atmosphere in the unit to cooling fins, built into the aluminum housing, where radiation will transfer the excess thermal energy to the Earth and deep-space. Therefore, with that given concept-of-operations, a general lumped capacitance thermal circuit can be realized, depicted in Figure 2.
Figure 2: ICU Lumped Capacitance Thermal Circuit Model

Note that albedo is related to the sunlight reflected off of the planet/moon, while Earth infrared (IR) is related to incident sunlight absorbed by the Earth and re-emitted as IR energy (or blackbody radiation). Each block in Figure 2 represents a lumped capacitance energy balance per Equation (6). Additionally, we can re-write $\dot{E}_{st}$ to Equation (2):\(^1\)

$$\dot{E}_{st} = \rho V C_p \frac{dT}{dt}$$ \hspace{1cm} (2)

Where $\rho$ is the mass density ($\text{kg/m}^3$), $V$ is the spatial volume of the thermal material ($\text{m}^3$), $C_p$ is the specific heat at constant pressure for a material ($\text{J/kg K}$) and $dT/dt$ is the change in temperature with respect to time ($\text{K/s}$). It should be noted that $\dot{E}_{st}$ can be rewritten as:\(^1\)

$$\dot{E}_{st} = MC_i \frac{dT}{dt}$$ \hspace{1cm} (3)

Where $MC_i$ is the product of mass density, $\rho$, volume, $V$, and the specific heat of the thermal material under analysis. In all, $MC_i$ becomes a simplification term for processing transient and steady-state solutions. Equation (3) is utilized in the context of the overall system model wherein each thermal element is linked by a heat transfer mode (i.e., convection links the PC/104 cards and the bulk nitrogen gas whereas radiation links the external ICU aluminum housing and the environment, etc.). Other terms in the model also need to be broken down as well, including the first convection term, rewritten in Equation (4):\(^1\)

$$\dot{E}_1 = h_1 A_1 (T_{CPU} - T_{GN2})$$ \hspace{1cm} (4)

Where $h_1$ is the convection coefficient with respect to the PC/104 stack ($\text{W/m}^2 \text{K}$), $A_1$ is the convection flow surface-area ($\text{m}^2$; again, over the PC/104 stack), and $T_{CPU}$ / $T_{GN2}$ are the temperatures of the CPU and nitrogen (K), respectively. Likewise, the second convection term can be broken out to Equation (5):\(^1\)

$$\dot{E}_2 = h_2 A_2 (T_{GN2} - T_{AL})$$ \hspace{1cm} (5)

Where $h_2$ is the convection coefficient with respect to the aluminum housing heat-sink cooling fins ($\text{W/m}^2 \text{K}$), $A_2$ is the convection flow surface-area ($\text{m}^2$; again, over the cooling fins), and $T_{GN2}$ / $T_{AL}$ are the temperatures of the nitrogen and aluminum housing (K), respectively.

Heat transfer exiting from the ICU can only, as assumed earlier, be conducted through radiation. Additionally, a small input to the thermal energy load will come from solar irradiance, and Earth infrared inputs (on average). Therefore, because radiation is our primary mode of heat transfer out of the system, the analysis must begin by assessing the physical phenomena in that region (i.e., radiative heat transfer surface) first, and then work backwards toward the primary heat-generation source (e.g., the CPU). These inputs and outputs can be broken up as laid out in Equations (6) through (9):\(^1\)

$$q_{space} = \varepsilon A \sigma (1 - f) (T_{AL}^4 - T_{space}^4)$$ \hspace{1cm} (6)

$$q_{earth} = \varepsilon A \sigma (f) (T_{AL}^4 - T_{earth}^4)$$ \hspace{1cm} (7)

$$q_{albedo} = A l_{solar} \rho_{albedo} F_{albedo}$$ \hspace{1cm} (8)

$$q_{space} = \varepsilon \ I_{EIR} F_{EIR}$$ \hspace{1cm} (9)

Where $\varepsilon$ is the emissivity of the radiative surface (unitless), $f$ is the view factor (unitless), $\sigma$ is the stefan-boltzman constant, $A$ is the radiation surface area ($\text{m}^2$), $T_{AL}$ is the aluminum temperature (K), $T_{space}$ is the temperature of empty-space (typically 3 K), $T_{earth}$ is the temperature of Earth (typically 293 K), $\alpha$ is the absorptivity factor (unitless), $I_{solar}$ is the solar flux ($\text{W/m}^2$), $I_{EIR}$ is the Earth IR flux ($\text{W/m}^2$), $\rho_{albedo}$ is the Earth's albedo, and $F_{albedo} / F_{EIR}$ are geometrical terms, based on the angle of the face to the sun and Earth (unitless).

The nadir view factor, $f$, is calculated according to the spherical geometry, associated with Figure 3.
The geometrical calculations which relate to Figure 3 are found below in Equations (10) to (14).

\[ R_{\text{satellite}} = R_{\text{earth}} + h \]  
\[ \theta = \sin^{-1} \frac{R_{\text{earth}}}{R_{\text{satellite}}} \]  
\[ r = R_{\text{earth}} \cos \theta \]  
\[ H = \frac{r}{\tan \theta} \]  
\[ f_{\text{earth}} = \frac{\pi r^2}{\pi r^2 + 2\pi r H} \]  

Where \( R_{\text{earth}} \) is the radius of the Earth (km), \( h \) is the altitude of the satellite (km), \( \theta \) is the half-angle horizon view point from the sensor (degrees), \( H \) is the maximum height from the orbit altitude to the earth-tangent point (km), \( r \) is the radius of the cylinder created with \( H \) as the cylinder length (km), and \( f_{\text{earth}} \) is the earth-facing view-factor (unitless). Note that the space-facing view factor can be related by Equation (15).

\[ f_{\text{space}} = 1 - f_{\text{earth}} \]

Continuing to work backwards to the thermal source, the next step in the thermal circuit is that of the conduction through the aluminum wall from the thermal transport fluid (dry nitrogen) to the radiative wall. Equation (16) is used to calculate that conduction thermal resistance.

\[ R_{\text{conduction}} = \frac{L_{\text{wall}}}{k_{\text{Al}} A_2} \]  

Where \( L_{\text{wall}} \) is the thickness of the thermal barrier (m; aluminum housing), \( k_{\text{Al}} \) is the thermal conductivity (W/m K) and \( A_2 \) is the conduction surface area (m²).

Next, assessment of the convection coefficient for heat transfer from the thermal fluid (nitrogen) to the aluminum housing, or \( h_i \) from Equation (4) or (5), needs to be determined. For maximum thermal pickup at this interface, it was prudent to design a heat-sink into the aluminum housing via cooling fins (allowing for a higher surface area for this transfer to take place). Initially, we must identify the geometry parameters for modeling purposes, depicted in Figure 4 (the general layout for the heat-sink modeling layout).
\[ A_{total} = NA_{fin} + A_{base} \quad (20) \]

\[ A_{channel} = L[S - t] \quad (21) \]

Also important to this assessment will be the perimeter, hydraulic diameter and overall area, calculated by equating Equation (22) through (24).1

\[ P = 2(L + S - t) \quad (22) \]

\[ D_h = \frac{4A_{channel}}{P} \quad (23) \]

\[ A = 2NLB \quad (24) \]

Now that geometry is understood, we begin the fluid-flow heat-transfer calculations, all utilizing thermophysical properties of nitrogen (assumed at 20 degrees Celsius and 18 psia). The mass flow rate is determined via Equation (25).1

\[ \dot{m} = \rho \dot{V} \quad (25) \]

Where \( \rho \) is the mass density of the nitrogen (kg/m\(^3\)), \( \dot{V} \) is the volumetric flow rate of the fluid (m\(^3\)/s) and \( N \) is the number of channels within the heat sink (unitless). Note that constant flow was assumed in this process. Additionally, without the aid of a detailed computational fluid dynamic analysis, an assumption of 40% of the volumetric flow rate from the DC fan can be expected within the ICU (conservative estimate). A suitable approximation for the mass density, \( \rho \), can be found using the ideal gas law in Equation (26).1

\[ \rho = \frac{P}{RT} \quad (26) \]

Where \( P \) is the absolute pressure (Pa), \( R \) is the universal gas constant and \( T \) is the fluid absolute temperature (K).

Upon determining the mass flow rate, the Reynolds number may subsequently be found for an internal flow-field in order to determine whether we are dealing with a laminar (Re < 2300) or turbulent (Re > 2300) flow. Equation (27) calculates this parameter.1

\[ Re_D = \frac{\dot{m}D_h}{\mu A_{channel}} \quad (27) \]

Where \( \dot{m} \) is the mass flow rate of the fluid (kg/m\(^3\)), \( D_h \) is the hydraulic diameter (m), \( A_{channel} \) is the frontal area of the channel (m\(^2\)) and \( \mu \) is the fluid viscosity (kg/s m). The final step prior to determination of the convection coefficient is to ascertain the value of the Nusselt number, which can be found utilizing Equation (28).1

\[ Nu_D = 0.023 Re\_D^{3/4} Pr^n \quad (28) \]

Where \( Re_D \) is the hydraulic diameter variant of the Reynolds number (unitless), \( Pr \) is the Prandtl number based on thermophysical property data of the fluid (unitless) and \( n \) is a correction power based on whether the fluid is being heated (n=.4) or cooled (n=.3). Also, it should be noted the Equation (28) is strictly utilized for a turbulent flow situation. Finally, Equation (29) can be used to determine the convection coefficient.1

\[ h = \frac{k}{D_h} Nu_D \quad (29) \]

Where \( k \) is the thermal conductivity of the fluid based on thermophysical material properties (W/m K), \( D_h \) is the hydraulic diameter (m) and \( Nu_D \) is the Nusselt number (unitless). Additionally, note that this process can be utilized for both the design of the aluminum housing cooling fins as well as for the PC/104 computer stack as the nitrogen passes over each.

In conclusion, these equations are used to balance and build the thermal model in order to characterize the system behavior over time from an initial state. Additionally, as the TCU design matures, this validated work will allow for further trade-space mapping. Next, discussion of the characterization campaign is discussed.

CHARACTERIZATION METHODOLOGY VIA DESIGN AND TEST

Model Design Methodology

As stated earlier, the rationale behind the characterization campaign was to assess the design under maximum predicted environmental loading and validate the thermal mathematical model. First and foremost, assessment of the orientation of the ICU upon this space payload is critical. From preliminary concept modeling of the space-based CTEx imaging platform, it was decided that the ICU will currently be oriented in a nadir-facing orientation along with the TCU due to the higher-level of confidence that this will be an unobstructed radiation emission path (as ISS requirements dictate that conduction into the structure and radiation to another device on-board the ISS is strictly prohibited). Figure 5 depicts the intended orientation of the ICU.
Because of this configuration, it is intentional that the ICU be designed as a stand-alone unit, meaning that upon applying power to the device, it will perform its mission (accepting commands, commanding the instrument, and saving/transmitting mission data as necessary) and it will be passively cooled via radiation. Therefore, one face will need to be purposely designed as a radiation surface to support the design intent (i.e., high emissivity with low absorptivity). Note that, even with a high emissivity, the radiation heat transfer is governed by the exterior surface temperature, per Equation (6) and (7), wherein it follows a profile similar to Figure 6.

The next feature of interest is the forced-convection fan which circulates the dry nitrogen atmosphere within the ICU at 18 psia. The Orion OD1238-24HB direct-current fan was selected for the high-level of throughput it produces while consuming minimal electrical power. Operating between 24 to 28 volts DC and roughly 4.8 watts, this device outputs 226 cubic feet per minute airflow at a nominal 65,000 lifetime-hours (at 45 °C). Note that its temperature operating range is between -10 and 70 °C. A support bracket was designed for the fan from aluminum 6061-T6 which fastens directly to the aluminum housing with spring washers (to prevent loosening during launch/ops). Figure 8 presents the aforementioned components.

The PC/104 card cage and vibration isolation system is a COTS item procured from Parvus Corporation and is called their PC/104 Card Cage with Shock Rocks©. This system is rated for military applications and utilized a novel securing mechanism to hold the PC/104 cards in place (through squeezing an elastomeric material in its corner). The Shock Rocks isolate the system from vibration by acting as a low-pass filter and are fastened directly to the card cage. Securing this system into the housing is accomplished through strategic placement of translation isolators (toleranced boss features in the housing to prevent motion). These translation isolators compress the Shock Rocks by approximately 2% in order to assure a positive compression upon these components (however, this internal compression does not affect the PC/104 card cage stack/structure and electronic components). Figure 7 depicts this arrangement.
Figure 8: ICU Convective-Flow Fan Assembly
The hermetically sealed electrical feedthrough is a face-seal, o-ring assembly supporting 12 pins at 20 AWG. This component was acquired through Pave Technology, Co. wherein each are delivered sealed with accompanying data specification documentation (required for space-traceability). Helium leak checks as well as Hypot electrical testing is accomplished upon each of these devices at the factory providing confidence to end-users of their pedigree for operations.5 Figure 9 presents the feedthrough configured within the ICU -- note the direction of assembly is critical for proper, long-term, on-orbit operations.

Figure 9: ICU Electrical Feedthrough
The fill/purge hand valve is a Swagelok SS-4BW stainless steel bellows valve rated to above 200 °C and 500 psig (note this design is not intended to attain these high levels of operation). It was selected for its compact size, durability and ability to perform pressure and vacuum service in both directions of flow (required for our concept of operations). The valve connects to the ICU via a welded VCR fitting to a 1/8-inch National Pipe Thread bore in a special feature designed into the aluminum housing known as a “doghouse.”6 A custom mounting bracket was designed directly into the housing to secure the device. After assembly of the ICU, this valve is operated to allow leak check and purge operations to be performed (to remove air containing oxygen, moisture, carbon dioxide and other contaminants) through connecting a vacuum pump for purge cycles to be completed. Roughly 10 purge cycles are acceptable for space-flight operations (pressurize to 30 psig followed by venting and vacuum-pumping down to 26 inches of mercury). Once the above-stated operations are completed, the valve handle may be removed and lock-wire shut as pre-launch operations continue. Figure 10 displays the purge/fill valve.

Figure 10: Swagelok SS-4BW Purge/Fill Hand Valve
The seal is a viton (fluorocarbon) o-ring, compatible for space-flight operations. This component was designed to integrate directly with the aluminum housing as a static face-seal gland wherein sizing and tolerance specifications were supported through manufacturer guidelines. Gland dimensions were set and adjusted to ensure that a 5-8% face squeeze is applied to the seal and a circumferential 2% squeeze is allowed (on the inner diameter of the o-ring) to support proper assembly. Additionally, a very thin layer of vacuum compatible grease was selected to be applied to the o-ring to support the seal at the temperature range expected (Castrol Braycote® 600EF).7 Figure 11 details the o-ring assembly.

Figure 11: ICU O-Ring Gasket Face-Seal
The aluminum housing is the most critical element in this assembly as it both supports all of the structural aspects of the device as well as promotes the proper thermal dissipation for normal operations. The housing front face is integrated with cooling fins and a thermal baffle supporting positive-compression of the PC/104 vibration isolation system as well as ensuring proper...
thermal loop flow direction. The positive-compression on the PC/104 stack is critical to ensure that the structure does not translate or rotate within the device. Moreover, a proper thermal loop flow direction is crucial so as not to develop “hot-spots” (i.e., pockets of stagnated flow). Design of the cooling fins was not optimized due to the fact that the final PC/104 stack composition (and thermal load) was not known at the time of design. Light-weighting was performed on the unit to acquire mass figures as low as possible while retaining structural safety margins. The housing elements are secured with 40 individual fasteners spread out at one-inch intervals due to the fact this is a low-pressure pressure vessel (18 psia). Maintaining this device as an “ambient-pressure” device is critical for the CTEx program in order to reduce prelaunch and on-orbit safety concern. Figure 12 details these components.

Figure 12: ICU Housing and Final Assembly

Test Campaign Methodology

The test campaign, to characterize nominal ICU operations, consisted of three primary phases, including: assembly/checkout, vibration and thermal-vacuum (TVAC) environmental loading. Each phase was intended to validate preliminary expectations for the performance of the device in order to provide confidence in the design as-built.

The assembly and checkout operations are critical in validating the basic mechanical and electrical functionality of the ICU. Detailed procedures for this phase were established with two overarching efforts, including the proper assembly/construction process, as well as leak check, purge and fill operations. Upon successful assembly, the device must be assessed for its leak rate. The leak-rate test is accomplished through setting up the configuration detailed below, wherein the ICU is connected to a pressure source (gaseous, dry nitrogen; i.e., GN2 K-Bottle), GN2 regulator, pressure gauge (PG-1) and valves (HV-1, HV-2, HV-3, GN2 Isolation HV). See Figure 13 for further detail.

Figure 13: ICU Leak-Check, Process and Identification Diagram

The leak check is conducted through slowly increasing the pressure at 10 psig increments from 0 to 35 psig (isolating the source pressure through closing the tank valve or regulator), holding each pressure-level for one minute, then elevating to the next set point, and holding the final test pressure (35 psig) for five minutes. Leak test solution is utilized to determine locations of spot leaks. If found, the system must be depressurized and the issue resolved prior to continuing. When no leaks are witnessed and the remaining process is accomplished satisfactorily, the test team may proceed.

The next operation which must be executed is the purge and fill of the ICU. The intent here is to ensure a high-purity thermal convective fluid exists within the device, allowing for low levels of contaminants (e.g., humidity, oxygen, carbon dioxide, etc.) as well as assisting in the designer’s ability to better predict the behavior of the unit. To execute the purge/fill, the previous apparatus setup is reconfigured with a vacuum pump (for this operation, an Edwards two-stage pump was selected, capable of .005 torr vacuum levels) and a three-way flow valve to be placed in line (in order to enable selection of purge or vacuum operations). Note that the earlier system for leak check may be setup into this final configuration in order to save time. Figure 14 depicts this updated configuration.

Figure 14: ICU Purge & Fill, Process and Identification Diagram
A minimum of ten vacuum/pressure cycles were conducted from 26-28 inches of mercury to 30 psig, respectively, to ensure the proper purge levels have been attained. Upon completion of the final fill cycle to 30 psig, the source valving (tank valve and regulator) will be closed and the remaining downstream system vented down to roughly 3-4 psig (~18-19 psia), leaving a low “pad-purge” on the system. This pad-pressure continues to keep internal positive pressure on the system while at ambient conditions as well as enabling users to witness leaks, should they occur during pre-launch and on-orbit operations. Completion of this set of operations allows for final electrical checkout, upon closeout of mechanical validation, prior to further integration of this device into the larger CTEx instrument assembly.

The second phase of this test campaign is that of maximum predicted environmental loading (MPEL) beginning with vibrational testing. The ICU sub-system was characterized utilizing the H-IIB Transfer Vehicle (HTV) Cargo Standard Interface Requirements Document (NASDA-ESPC-2857 Rev.C). The primary goals of this phase were to understand the modal properties of the ICU (natural resonances) and validate functionality after each test run had been conducted. All three axes of the ICU were excited following a pattern of sine-sweep (.25g level), random vibration (three minutes duration per the ISS Qualification and Acceptance Environmental Test Requirements, SSP 41172 Revision U, and HTV Cargo Standard Interface Requirements Document, NASDA-ESPC-2857 Rev. C), final sine-sweep (.25g level, to assess changes from the initial) and a functionality test (cycling power, assessing all electrical/sensor functionality, and mechanical pressure is held). After all portions of this phase were complete, the ICU was opened to assess internal issues (visual inspection).

Finally, the last portion of the ICU test campaign consisted of the TVAC operations to both assess the ability to operate in a vacuum environment as well as to characterize thermal behavior (while cycling and controlling the environmental temperature it operates within). The intent of this effort was to validate thermal behavior while adjusting the input parameters (TVAC temperature and ICU electrical power). Vacuum levels are set to those witnessed during nominal, space-flight operations (~1E-6 torr). Set points for input power and external thermal environment were determined through assessing low-, mid-, and high-range expectations for operational scenarios. Regarding electrical input power, these parameter set points were 13 watts (low), 25 watts (mid) and 40 watts (high). TVAC thermal-environment loading was characterized at -40 °C (low), 20 °C (mid) and 40 °C (high) levels. Test operations were executed by allowing the system to start at an initial (cool) state, then applying power and temperature to monitor the transient reaction of the device. After an adequate period of time or a threshold temperature was attained (e.g., CPU temperature at 85 °C), the power was disabled for cooling operations to begin in order to recycle to the next set point. Within the TVAC chamber, the ICU was setup to only allow radiation as the means for thermal dissipation (through insulating the bottom of the unit from the TVAC platen with a sheet of one-inch delrin). TVAC electrical feed-throughs allow for independent power to be connected to the CPU, fan and resistive heater-patch (enabling selective control over the operations of this phase of the characterization), as well as, external thermocouples to monitor thermal flux and internal temperature levels. Figure 15 depicts the TVAC test setup.

**RESULTS**

ICU data resulting from the design, analysis and test campaign is broken into three segments including: modeling expectations, test campaign products and on-orbit predictions.

**Modeling Expectations**

Due to the fact that this developmental work is centered around a model validation focus, a moderate amount of research effort was expended determining a suitable model to meet early trade-space requirements. From the methodology setup earlier, a MATLAB Simulink ® mathematical model was developed to study the transient and steady-state effects of various set point conditions for the ICU. See Figure 16 presenting the Simulink model.
From an early point in the design, it was understood that even moderate power levels will cause high thermal conditions, likely exceeding thresholds deemed as “safe” (through assessment of manufacturer technical data). Nevertheless, the primary input parameters for the thermal model include the external thermal environmental conditions (Earth, deep-space, or TVAC temperature), electrical power level input, and emissivity. Results from a representative run (ICU power at 13 W, TVAC temperature at -40 °C and surface finish is machined aluminum, $\varepsilon = 0.09$) are shown in Figure 17.

Results from a select number of runs are tabulated below in Table 1. It should be noted that these early results presented from this model are for the ICU testing within the TVAC chamber, radiating all energy off of five of its surfaces (i.e., a “best-case” scenario; versus on orbit, where likely only 2-3 surfaces will be permitted to dissipate excess energy through radiation).

The information that Table 1 supports is some of the early trade-space analysis needed to better define more rigorous design (as further requirements are refined) as well as provide for an early operational picture (i.e., how long we can execute operations at peak electrical load conditions). From this data, it can be witnessed that a surface treatment will be necessary if the design is utilized for on-orbit operations. Additionally, peak power consumption will be limited to 25 watts for limited periods of time (after which will need to be periods of cooling).

The next assessment performed was a cursory review of stress and modal properties associated with operational conditions. This activity focused on the ICU housing internal pressure, external pressure and modal analysis load cases, analyzed with the help of finite element modeling (FEM) wherein ANSYS ® was utilized. Note that this analysis was intended to verify, after significant light-weighting of the ICU assembly, that significant structural issues had not resulted, possibly causing failure under load (and to mitigate those, if found). Therefore, best-practice methodologies were utilized in this portion of the effort; however, an optimization and refinement of the results was not conducted (nor was it the goal to closely match the model to gathered laboratory results).

It was found that, after feature reduction of the CAD model to only the most critical aspects (primarily the housing elements and fan bracketry, removing holes and other non-essential geometry for modeling purposes), that a mesh size of 0.1 inch cubes (solids) was acceptable to converge to a solution. Load cases for the internal and external pressure were meant to assess the operational set points expected; however, additional pressure was added to the internal pressure load case to account for the purge and pressurization pre-launch operations. The external pressure load case was also meant to simulate the purge and pressurization...
load case in the scenario of vacuum operations (where a higher external pressure is witnessed). Thus, the internal pressure load case was set to 35 psia and external pressure load case was set to 14.7 psia. The modal analysis collected the first six non-rigid body modes.

Overall, results from this modeling effort were favorable. Worst-case loading in the internal pressure scenario accounted for a 12.64 ksi maximum stress and 0.0048 inch displacement at the rear-side of the ICU housing. The selected material (aluminum 6061-T6) was deemed acceptable as yield strength is 45 ksi (roughly a 3.5 safety factor). See Figure 18 for the post-processed plot for this load case. The external pressure load case (during pressure/vacuum purge cycling) was significantly lower at 5.755 ksi and maximum displacement at 0.002 inches predicted (again, acceptable in light of the previous discussion). Figure 19 details the post-processed results from this operational analysis. Finally, an eigenvalue analysis was performed to determine the modal response of the ICU structure. From this analysis it was determined that the first structural natural frequency is expected to be at 386.2 Hz. These results are acceptable as the initial natural resonance mode needs to be greater than 50 Hz to meet specifications for launch.

![Figure 18: ICU FEM, Max Displacement (in), Internal Pressure Load Case, 35 psia](image)

![Figure 19: ICU FEM, Max Displacement (in), Ext Pressure Case, 14.7 psia](image)

---

**Test Campaign Outcome**

As discussed earlier, the intent of the test campaign was to validate the mathematical thermal model as well as assess whether the design met feasibility thresholds for expected operational mission constraints. The initial qualitative results acquired from the test campaign were in the assembly process. Through only minor corrections in the mechanical design, the most major issue resulted from a convenience in the fabrication process of the ICU housing. Due to the geometry of the Parvus Shock Rocks®, the translation isolators in the ICU aluminum housing originally called for a non-radius/square corner; however, a simple solution was found to modify the Shock Rocks through allowing the housing machine radius and adding a 1/8 inch chamfer to the shock rocks. See Figure 20 for further detail.

![Figure 20: Parvus Card Cage Reconfiguration](image)
the requirements that it must fall under 10 kg. Figure 21 depicts the assembly processing.

Figure 21: ICU Assembly

The vibration phase of the test campaign resulted in positive results as well. The fundamental frequency resulted at 376 Hz, roughly 2.7% from the FEM predictions (386.2 Hz – due to excitation of the fan/bracket assembly). This also surpasses the modal requirement to ensure the fundamental frequency is above 35 Hz (in all directions for this design). The functionality of the electronics and the ability to mechanically retain pressure also passed successfully without any issue to report. One primary issue experienced was that of fasteners loosening during random vibration testing, especially at metal/plastic interfaces, such as the fan bracket (even though locking spring-washers were used throughout the design). This issue could be resolved through application of a vacuum-compatible thread-locking fluid to fasteners. Figure 22, 23, and 24 details the modal testing for the X, Y and Z axes under test, respectively.

Figure 22: SCTEx ICU, 0.25g Sine-Sweep, X-Axis

Finally, results from the TVAC phase exceeded expectations pertaining to the thermal modeling validation. In general, this phase of the test campaign ran as seamless as the other phases; however, there were noteworthy issues. First, and most notable, were complications relating to connectivity with the PC/104 stack. It was concluded that inexpensive electronics in the configuration were attributable to a repeated dropout problem as it was witnessed especially during periods with higher loading placed upon the ICU (both power and thermal set-points). These dropouts forced the test series to only collect data at low- and mid-range CPU power levels. Next, it was witnessed that the PC/104 weather board selected also had an issue with respect to the maximum pressure it could sense (130 kPa, or 18.85 psia). Therefore, as temperature was elevated and the pressure also increased (due to ideal gas behavior of the fluid), over-ranging values were acquired. Nevertheless, during cool-down periods of testing, pressure measurements re-entered a suitable range (and provided confidence that pressure had not been lost within the ICU). Finally, an issue was also witnessed on this weather board as gaseous-nitrogen fluid temperature measurements were acquired. The nitrogen fluid temperature was consistently measured 5-10 °C below expectations throughout the test campaign (and may be potentially coupled to the over-ranged pressure measurements). This error may have been caused by other factors, including: thermocouple
calibration, the device temperature ramping up (i.e., not at steady state), and some combination of the fluid and a nearby PC/104 board, among other rationale.

Figure 25 shows a cold run (low TVAC temperature, -40°C) and low power level (13 W) with both actual and simulated results overlaid. Figure 26 depicts the error (in degrees, acquired measurements versus simulation). As noted earlier, the nitrogen temperature is offset by 4°C; however, the measured CPU and aluminum housing temperatures match within nearly 1% that of the simulation for the duration of the nine-hour test. The model emissivity parameter is set for machined aluminum (ε = 0.09).

From this data, it is again witnessed a -6 °C offset in the nitrogen temperature whereas the CPU and aluminum housing temperature offset is roughly 2 °C (negative due to the fact that the model predicts a lower temperature than what was witnessed). Although there is a noticeable offset, it should be noted that the slopes for each of these curves match very closely to one another. A general slope of +4.4 °C per hour was witnessed overall.

Figure 27 presents a nominal run at mid-range temperature and low-power levels (20 °C and 13 W, respectively) while Figure 28 shows the error (in degrees, acquired measurements versus simulation). The final run presented in Figure 29, corresponds to a nominal/mid-power level (27 W) and a mid-temperature setting (20 °C) while Figure 30 shows the error (in degrees, acquired measurements versus simulation). From this profile, again, the nitrogen average offset is -8.86 °C, CPU is -7.1 °C and aluminum block is 2.89 °C. Some of this error is attributable to the fact that all 27 W is applied to the CPU in the mathematical model, whereas during the
test run, 13 W was applied to the CPU and fan, while the remaining 14 W was applied to the resistive heater patch.

assess the steady-state peak temperatures. In general, roughly a positive two-degree offset was witnessed to be the worst-case differential temperature while comparing measured data from model outputs (recall that transient slopes matched closely allowing the offset to correct for final thermal differences). Additionally, the model was reverted from the TVAC thermal case to that of the on-orbit configuration (most notably, two primary radiation faces and blackbody environmental temperatures of 293K and 3K for the Earth and deep-space, respectively). Additionally, due to the design benefits, ZOT white paint was selected as the ICU surface coating to improve thermal behavior characteristics (emissivity = .91, absorptivity = .17).

Results from the model corrections can be seen for ICU input-power cases of 13W and 25W in Figure 31 and 32, below. As expected, the 25W load case surpasses initial thresholds (85°C) after roughly a 1.5 hour period (from an initial state of 20°C).

On-Orbit Predictions

Overall, from the results gathered during the TVAC phase of testing, validation of the thermal mathematical model was determined to be successful (given, that factors are applied to account for minor offsets). Due to the validation of the thermal transient slopes, it is expected that steady-state conditions should be witnessed at a minimum of +/- 10% final equilibrium temperatures. Therefore, with this validated model, assessment for on-orbit predicted behavior and mapping the initial trade-space may continue.

To begin, we will first apply correction factors to the three cases reviewed in the previous sub-section and

Figure 29: SCTEx ICU Temperature Profile, Measured Vs. Simulated, 27W/20C

Figure 30: SCTEx ICU Error Profile, Measured Vs. Simulated, 27W/20C
CONCLUSIONS

In this research, mathematical models were developed and an early design was built to validate the ICU which is intended to support the space-based CTEx instrument. Requirements for this design were centered around COTS electronics in a hermetically sealed structure meeting launch and on-orbit requirements. The design methodology incorporated concepts currently in operation on-orbit and decisions which accommodated the current CTEx mission CONOPS.

Figure 33 is a photo of the fabricated and assembled ICU. The aluminum housing was fabricated at the AFIT model shop requiring roughly 150 hours of machine time over the course of two months. Upon acquisition of all necessary components, the final ICU assembly was accomplished seamlessly over the course of two days and according to a standard operating procedure. Included in these assembly procedures was a leak check and purge cycle which also ran according to plan (no leaks or other significant mechanical issues were witnessed during this processing).

Performance assessments were accomplished after final assembly, including operational checkout, vibe-table and thermal vacuum testing. The system operated as expected during operational checkout with no significant issues to report. Vibe-table frequency response tests resulted in validating that the ICU can meet minimum threshold launch requirements (as fundamental frequencies are greater than 50 Hz). Finally, validation of the mathematical thermal model was acquired as measurements tracked to within +/- 3°C to those expected from simulations performed. Concern areas of note during this campaign include poor-performing electronics (e.g., the inexpensive “weather” board wherein multiple issues in dropouts, pressure over-ranging and erroneous nitrogen temperature measurements were witnessed) as well as the housing external surface coating (i.e., selection of a paint which increases emissivity and decreases absorptivity will greatly improve expulsion of excess thermal energy). Nevertheless, with the validated thermal model, predictions could be made for on-orbit operations (having changed parameters to include the emissivity, power input, and operating environment characteristics). The overall conclusion here is that the device may run indefinitely at a power level of 13W and should be limited to 3-4 hour segments at elevated (~25W) operating levels.

As future work, further detailed design needs to go into the PC/104 computer stack (as the system tested in this research was representative). Considerations for operational functionality, power, thermal and reliability are but a few requirements which need to be honed. Additionally, this effort needs to integrate development of the control electronics, software, and interface with the ISS/STP-provided C&DH system. The above areas will feed into further levels of downstream mission planning as the space-instrument design matures and incorporates the TCU development.

References