On-orbit Absolute Calibration of Temperature with Application to the CLARREO Mission

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ABSTRACT

NASA's anticipated plan for a mission dedicated to climate (CLARREO) will hinge upon the ability to fly absolute standards that can provide the basis to meet stringent requirements on measurement accuracy For example, instrumentation designed to measure spectrally resolved infrared radiances will require high-emissivity calibration blackbodies having absolute temperature uncertainties of better than 0.045 K (3 sigma). A novel scheme to provide absolute calibration of temperature sensors, suitable for CLARREO on-orbit operation, has been demonstrated in the laboratory at the University of Wisconsin. The scheme uses the transient temperature signature obtained during the phase change of different reference materials, imbedded in the same thermally conductive medium as the temperature sensors – in this case the aluminum blackbody cavity. Three or more reference materials can be used to assign an absolute scale to the thermistor sensors over a large temperature range. Using very small quantities of phase change material (<1/250th the mass of the cavity), melt temperature accuracies of better than 10 mK have been demonstrated for Hg, H_2O, and Ga, providing calibration from 233K to 303K. The flight implementation of this new scheme will involve special considerations for packaging the phase change materials to ensure long-term compatibility with the containment system, and design features that help ensure that the on-orbit melt behavior in a microgravity environment is unchanged from pre-flight full gravitational conditions under which the system is characterized.

Keywords: Absolute Temperature Calibration, Blackbody, Climate Mission

1. INTRODUCTION

Future NASA climate spaceflight missions such as the anticipated Climate Absolute Radiance and Refractivity Observatory (CLARREO) will hinge upon the ability to fly absolute standards that can provide the basis to meet stringent requirements on measurement accuracy. For example, instrumentation designed to measure spectrally resolved infrared radiances to detect a climate signature of 0.1 K per decade will require high-emissivity calibration blackbodies having absolute temperature uncertainties of better than 0.045 K (3 sigma). A key requirement for these future missions is to provide traceability to SI standards on-orbit.[1,2,3,4,5]

This emerging need provided the motivation to develop a simple, low mass, absolute temperature calibration system that could be incorporated into an existing spaceflight blackbody design – the on-board blackbody calibration system developed for NASA's Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument.[6,7] The engineering development model of the GIFTS has successfully undergone thermal vacuum functional testing and calibration at the Utah State Space Dynamics Laboratory.[8,9] The demonstrated state-of-the-art performance of the on-board blackbody system makes it nearly suitable for a CLARREO type climate mission. What is lacking is the on-orbit traceability to SI standards, such as ties to the melt points of standard reference materials for absolute temperature calibration, and the capability of make absolute reflectance measurements of the emitting surface. This paper describes a scheme to provide absolute calibration to temperature sensors that is suitable for an on-board blackbody system. A NASA Instrument Incubator Program (IIP) grant has been awarded to advance the technical readiness of this pioneering research to Technical Readiness Level (6), which will involve demonstration in a relevant environment.

This paper will start by describing the key features of the GIFTS on-board blackbody system that was used to demonstrate the new absolute temperature calibration concept. This will be followed by a detailed description of the

Earth Observing Systems XIII, edited by James J. Butler, Jack Xiong, Proc. of SPIE Vol. 7081,
70810O, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.795457

novel scheme to use the blackbody transient temperature signature, obtained during the phase change of small quantities of different reference materials imbedded in the cavity, to assign an absolute temperature scale to the blackbody temperature sensors. This will be followed by a discussion of the implementation and expected accuracy of the new scheme for use on a mission such as CLARREO, along with the research focus during the NASA Instrument Incubator Program.

2. GIFTS BLACKBODY SUBSYSTEM OVERVIEW

The GIFTS on-board blackbody calibration system consists of two blackbody sources and an externally located controller that provides independent temperature measurement and control for each blackbody.[10,11,12,13,14] The table on the left of Figure 1 provides the key parameters for this system, most notably the 3σ absolute temperature uncertainty of 56 mK, that is the projected value at the end of a 7 year mission. The blackbodies have an operational range between 233 and 313 K. The middle photo and cut-away view on the right of Fig. 1 illustrate the blackbody design, that is scaled from the University of Wisconsin (UW) developed Atmospheric Emitted Radiance Interferometer (AERI) blackbody,[15,16] scaled to a 1" aperture diameter to accommodate the GIFTS optical design. The blackbody cavities are machined from aluminum and painted with Aeroglaze Z306 diffuse black paint. Thermistor temperature sensors are used, each mounted in a customized threaded housing that screws into the aluminum cavity wall. Two of these thermistors are mounted near the apex of the cone and up to six others are mounted circumferentially near the junction between the cylinder and cone. The cavity has a thermofoil heater shown mounted circumferentially around the cavity cylindrical section.

Key Parameter	Specification	As Delivered
Measurement Range	233 to 313 K	233 to 313 K
Temperature Uncertainty	< 0.1 K (3 σ)	< 0.056 K
Blackbody Emissivity	> 0.996	> 0.999
Emissivity Uncertainty	< 0.002 (3 σ)	< 0.00072
Entrance Aperture	1.0 inch	1.0 inch
Mass (2 BBs + controller)	< 2.4 kg	2.1 kg
Power (average/max)	< 2.2/5.2 W	2.2/5.2 W

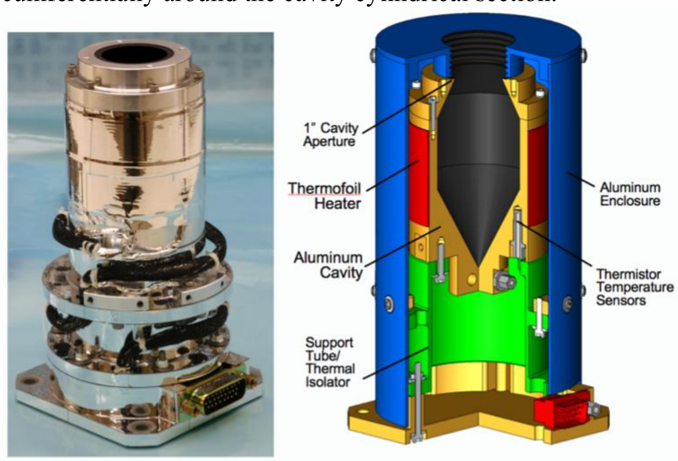

Figure 1. The GIFTS EDU blackbody top-level specifications and as-delivered performance are shown in table at left. A photo of the as-delivered hardware is shown in the middle without the enclosure. The cut-away figure on the right illustrates the key features of blackbody, including the thermistor locations and painted aluminum cavity.

The blackbody controller functional block diagram is presented in Figure 2. The controller provides independent temperature measurement and control for each blackbody, and operates in either constant temperature or constant power mode. In the constant temperature mode one of two redundant control thermistors is used for feedback. The difference between the feedback thermistor resistance and the programmable set point resistance is processed by an analog Proportional-Integral-Derivative (PID) circuit to determine the heater power required to achieve and maintain the desired temperature. A pulse width modulator (PWM) is used to drive the blackbody heater. Blackbody temperature stabilities of better than 2 mK over 80 minutes were demonstrated during a typical test cycle of the thermal vacuum calibration testing of the GIFTS instrument. In the constant power mode a set point integer controls the heater duty cycle. A total blackbody cavity heater power of 2 W is available with a set point resolution of 500 µW.

A key feature of the controller is the self-calibration scheme that employs the use of on-board reference resistors. These highly stable resistors are read each time the blackbody thermistor resistances are read, thus significantly reducing measurement uncertainty – measurement accuracy becomes largely independent of offset and gain drift of the electronics. The calibration of these on-board reference resistors is performed on the ground as part of the temperature calibration of the entire blackbody system.

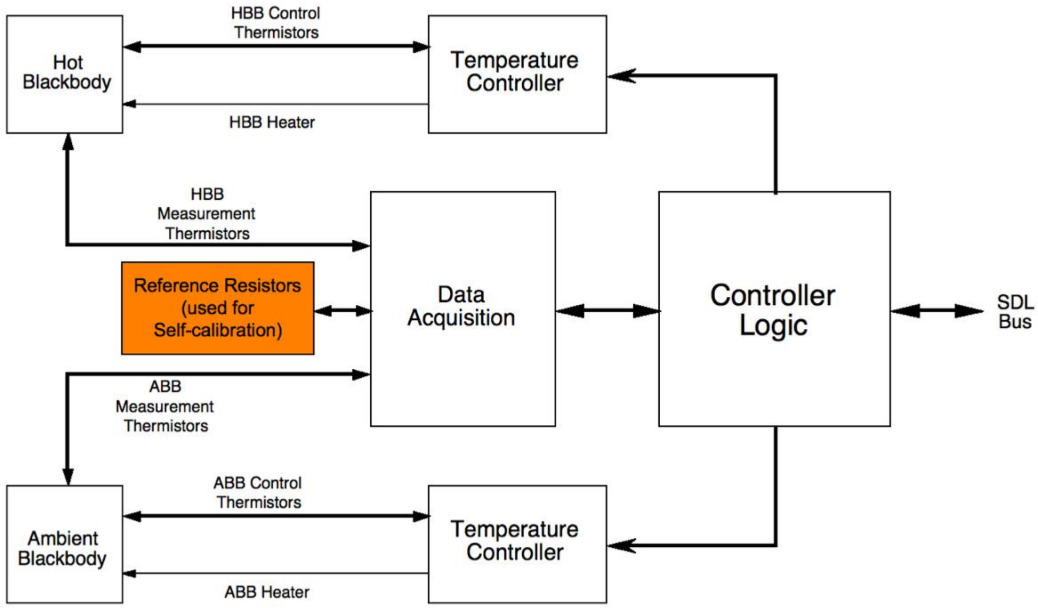

Figure 2. The blackbody controller provides independent temperature measurement and control for both blackbodies. At each data collection cycle the on-board reference resistors are measured along with the blackbody thermistor resistances – providing self-calibration.

3.0 A NOVEL SCHEME FOR ABSOLUTE TEMPERATURE CALIBRATION

The novel scheme for absolute temperature calibration is based on a new concept that is expected to have wide applicability for the remote temperature calibration of devices. It uses transient temperature melt signatures from three (or more) different phase change materials to provide absolute calibration for the blackbody thermistor sensors covering a wide, continuous range of atmospheric temperatures. The system uses very small masses of phase change material (<1 g), making it well suited for spaceflight application.

A prototype of this absolute calibration scheme using gallium, water, and mercury has been demonstrated at the University of Wisconsin under internal funding, using a duplicate of the GIFTS blackbody system. Figure 3 illustrates the modifications to the GIFTS blackbody design that were implemented to demonstrate the new scheme. The middle photo in the figure is a view looking into the back of the blackbody cavity showing the six possible circumferential locations for the custom packaged thermistors (shown in the right of the figure). The packaging for the small quantities of phase change materials closely resembles that of the thermistors – allowing them to be threaded into the cavity in similar fashion. Figure 3 illustrates the phase change material gallium; other phase change materials are packaged similarly, and are threaded into separate locations. For example, the existing GIFTS design allows three different phase change materials to be interleaved with three different thermistors.

Figure 4 shows a shows a typical transient temperature response of one of the blackbody cavity thermistors during a gallium melt event, where it can be seen that the melt plateau is clearly discernable to within 5 mK of the known melt temperature. Figure 5 illustrates the general sequence of events during a typical melt (a gallium melt is shown). First the blackbody cavity is brought to thermal stability in the constant temperature mode about 50 mK under the expected phase change temperature. Then the blackbody controller is switched into constant power mode using the power level that would bring the cavity to about 100 mK above the expected phase change temperature.

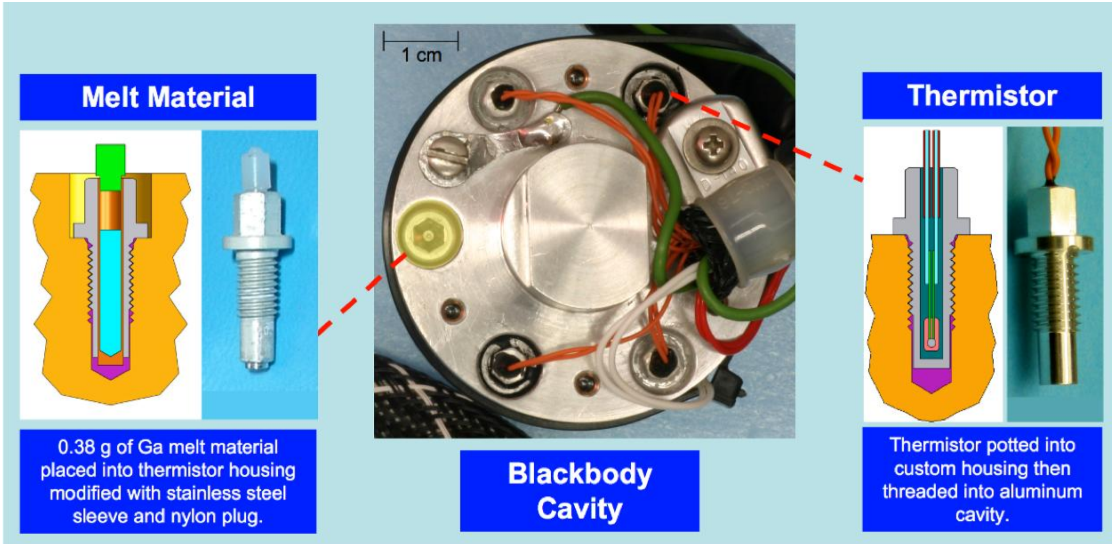

Figure 3. Configuration used to demonstrate the absolute temperature calibration concept, using a UW-SSEC mock-up blackbody. Small quantities (<1g) of different phase change materials are integrated into custom housings that have the same geometry as the temperature sensors. Threaded holes in the blackbody cavity accept either thermistors or one of the phase change materials (gallium is shown).

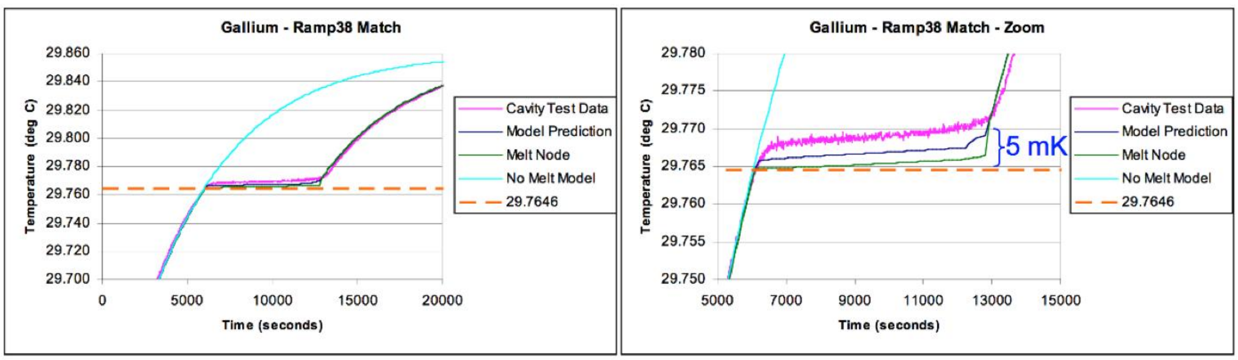

Figure 4. Typical gallium melt signature obtained with UW blackbody mock-up system. The plot on the right is an expanded view of the data potted on the left. The aqua colored rising exponential shows the temperature response of the blackbody cavity to constant power if no gallium were present. The plot on the right clearly shows that this melt event can be distinguished to within 5 mK.

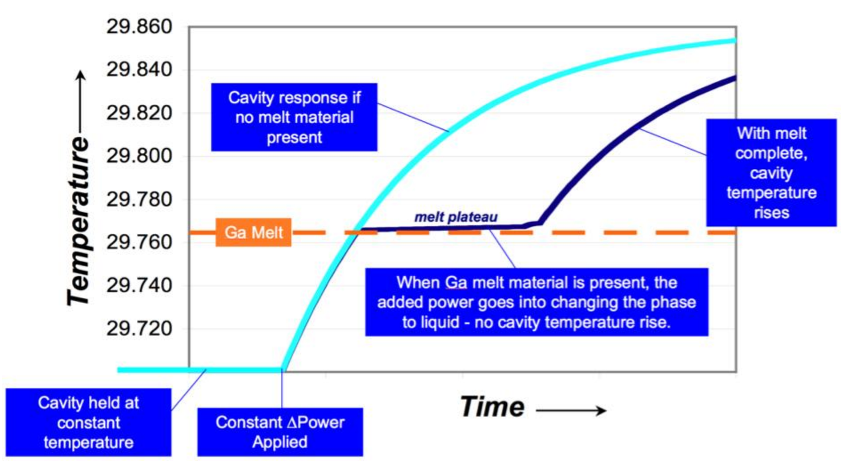

Figure 5. Sequence of events during a typical melt of gallium as configured in Figure 3. After initial stabilization in the constant temperature mode, a constant power is used to transition through the melt plateau.

Significant testing has been conducted to explore the melt plateau repeatability, and to characterize the relationship between the melt plateau temperature and the time taken to go through the melt. Figure 6 illustrates excellent melt plateau repeatability for five different runs that span a period of 9 months. The plot on the right is an expanded view of the data plotted on the left. The deviations between the ramps at the end of the melt arise from differences in the external temperature environment. Note that the peak-to-peak variation between runs is less than 2 mK over most of the melt.

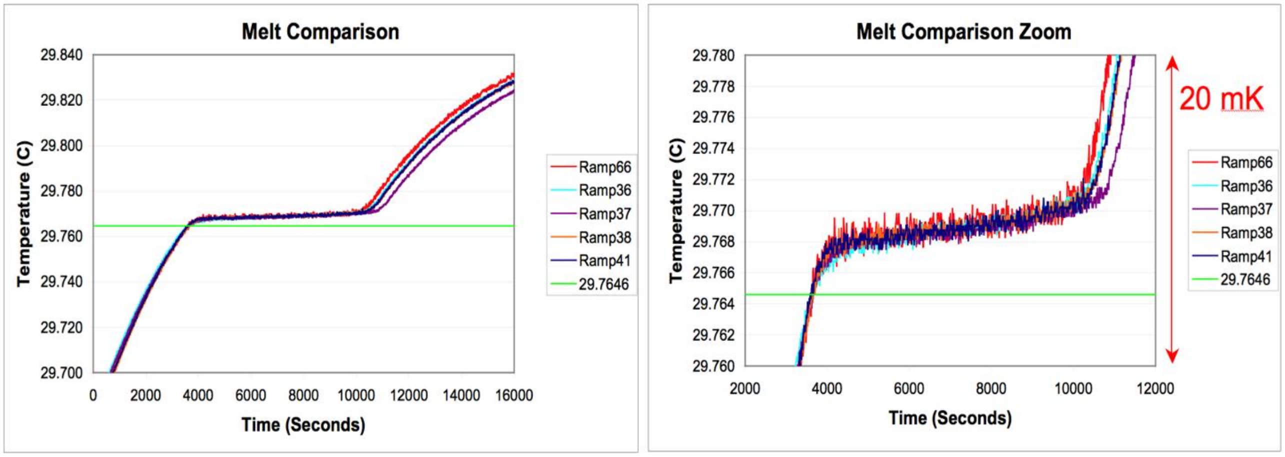

Figure 6. Repeatability of five different gallium melts is better than 2 mK. Melts spanned a 9-month period. The plot at right with a full scale of 20 mK is an expanded view of the data plotted at left.

Figure 7 presents three different gallium melts with durations lasting 5,000, 8,000, and 32,000 seconds. It can be seen that the longer duration melts have plateaus that more closely approach the gallium melt temperature. Figure 8 provides a comprehensive look at the relationship between plateau temperature and melt duration. The data asymptotically approaches a value within 1mK of the true gallium melt temperature. The different symbols in the plot represent different configurations of the temperature-controlled external environment. The yellow shaded data points near 6,000 seconds are the five ramps shown in Figure 6.

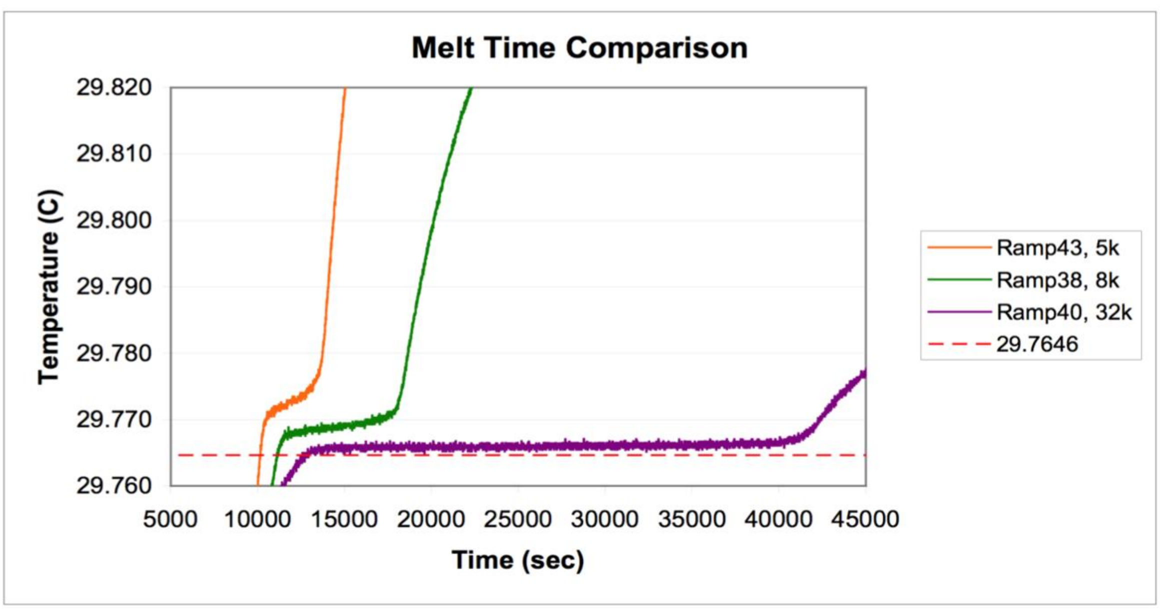

Figure 7. Gallium melts of different duration. The plateau temperatures of a melt more closely approaches the true gallium melt temperature for longer melt times.

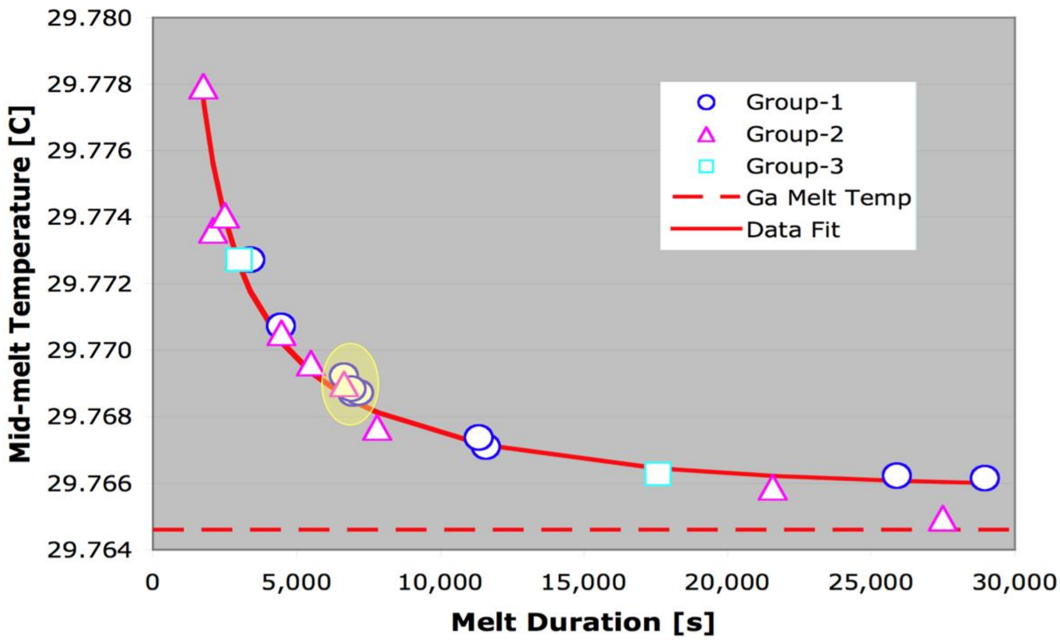

Figure 8. Gallium mid-melt temperature for 20 different melts of different durations. The data asymptotically approaches the true gallium melt temperature to within 1 mK at longer melt times.

A key limitation of this absolute temperature scheme is the fact that there are small temperature gradients in the cavity during the melt. The melt event that occurs within the cavity at the location of the small quantity of melt material must be transferred to the thermistor temperature sensors located throughout the cavity. Figure 9 illustrates that these gradients are indeed small (1.2 mK), even for a "fast" 4,800 second gallium melt. The plot at the lower right shows the temperature difference (during the melt) between two thermistors located at different distances from the gallium melt material.

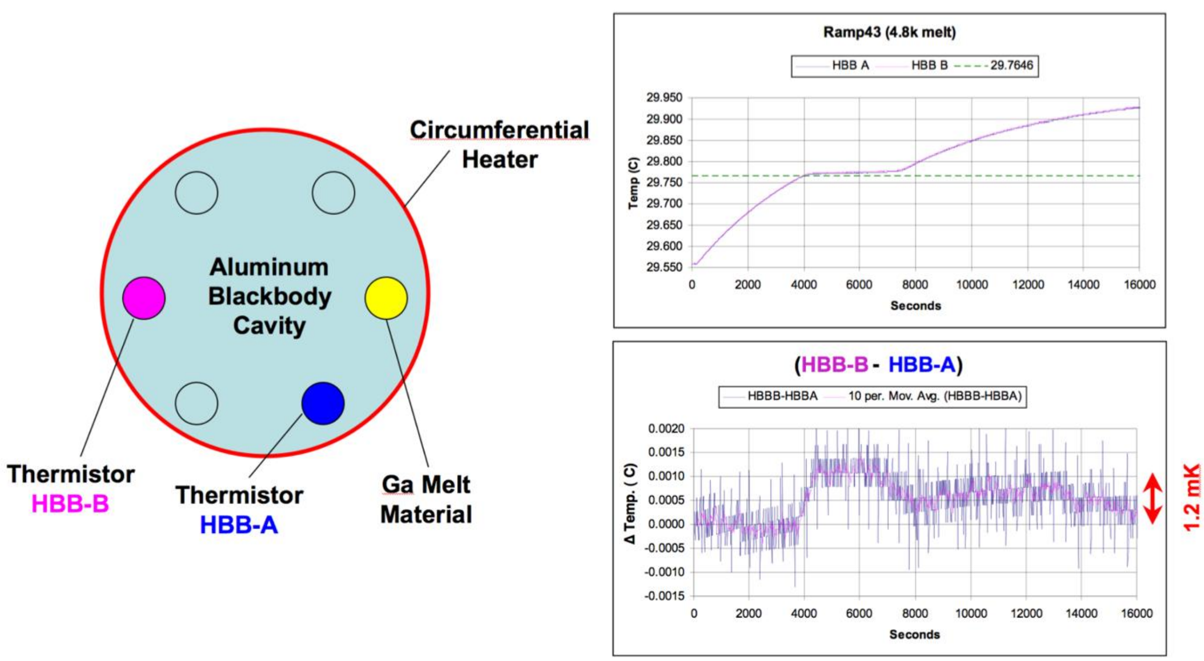

Figure 9. Gradients in the blackbody cavity during a "fast" 4,800 second melt are on the order of 1.2 mK. The lower right plot shows the temperature difference in the two thermistors located as shown in the figure on the left.

4.0 IMPLEMENTATION

The implementation of the absolute temperature scheme presented here requires straightforward modifications to the GIFTS blackbody spaceflight subsystem design. Figure 10 illustrates a blackbody cavity with small quantities of phase change materials (Ga, H_20, and Hg) imbedded in the cavity body, interleaved between the thermistor temperature sensors to be calibrated. The expanded view on the right of Figure 10 is an idealized version of the middle photo of Figure 3. The red lines in the figure located on the cavity and external enclosure represent heaters that provide the environmental control necessary to acquire melt signatures.

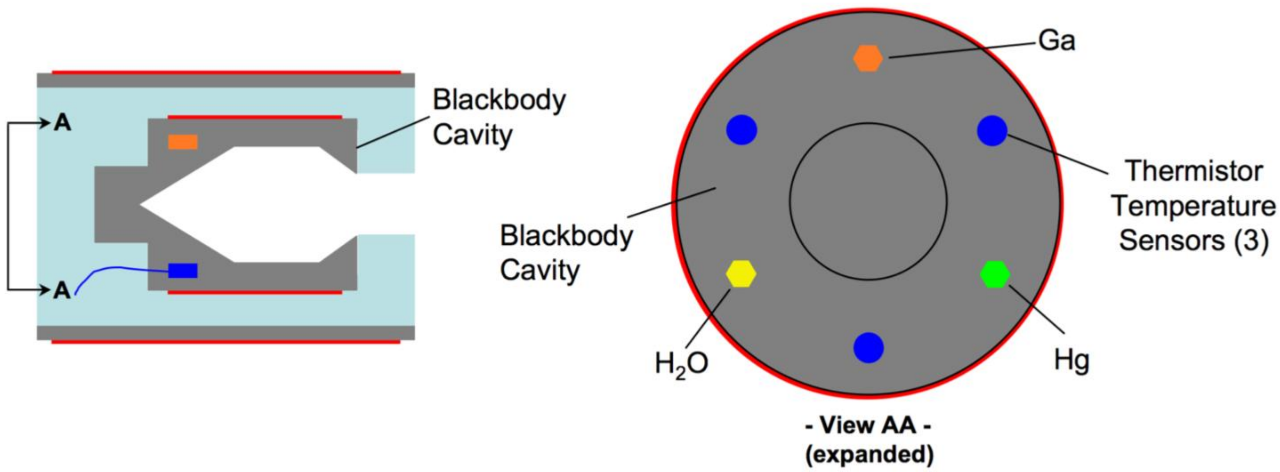

Figure 10. Implementation of the absolute temperature scheme requires integrating small quantities of different phase change materials into the aluminum blackbody cavity, interleaved between the thermistor temperature sensors to be calibrated. The view on the right is an expanded end view of the cavity only.

Calibration of the thermistor temperature sensors is conducted by sequentially transitioning through the melt temperature of each of the phase change materials, using the scheme outlined in Figure 5 to obtain the melt signature. At each melt plateau the resistances of the thermistors to be calibrated are recorded, in this case giving three pairs of calibration temperature and measured resistance for each thermistor. Thermistor temperature sensors can be well characterized using the traditional Steinhart and Hart equation which appears below along with the solution for the three calibration coefficients. In the matrix equation below, the subscripts represent data obtained at each of the three melt temperatures for Ga, H_20, and Hg.

$$\frac{1}{T} = A + B\ln(R) + C(\ln(R))^3$$

$$\begin{vmatrix} A \\ B \\ C \end{vmatrix} = \begin{vmatrix} 1 & \ln R_{Ga} & (\ln R_{Ga})^3 \\ 1 & \ln R_{H_2O} & (\ln R_{H_2O})^3 \\ 1 & \ln R_{Hg} & (\ln R_{Hg})^3 \end{vmatrix}^{-1} \bullet \begin{vmatrix} T_{Ga}^{-1} \\ T_{H_2O}^{-1} \\ T_{Hg}^{-1} \end{vmatrix}$$

The three-term Steinhart and Hart equation will represent true thermistor behavior to within 10 mK over the temperature range defined by the melt temperatures of gallium (29.77 °C), Water (0 °C), and Mercury (-38.87 °C). This 10 mK is the maximum residual between the Steinhart and Hart three-term and four-term equation (which is known to represent true thermistor behavior to within 1 mK) for a Thermometrics thermistor with a resistance of 2,200 ohms at 25 °C that follows Curve-7. If each of the three melt temperatures is established to within an uncertainty of 10 mK (3-sigma), the maximum uncertainty arising from the three-term fitting equation is less than 25 mK over the full range from -39 to 30 °C. These uncertainties can be lowered and the calibrated temperature range extended by using additional melt materials, such as gallium based eutectic alloys,[17] in conjunction with using a four-term Steinhart and Hart equation (add the squared term), or with a regression formulation of either the three or four-term Steinhart and Hart equation.

Figure 11 illustrates melt data obtained from mercury, water, and gallium to establish a temperature scale from -39 to +30 °C. For each of these melts, the phase change material was configured as is shown in Figure 3. The resulting melt plateau represents the true melt temperature within 10 mK.

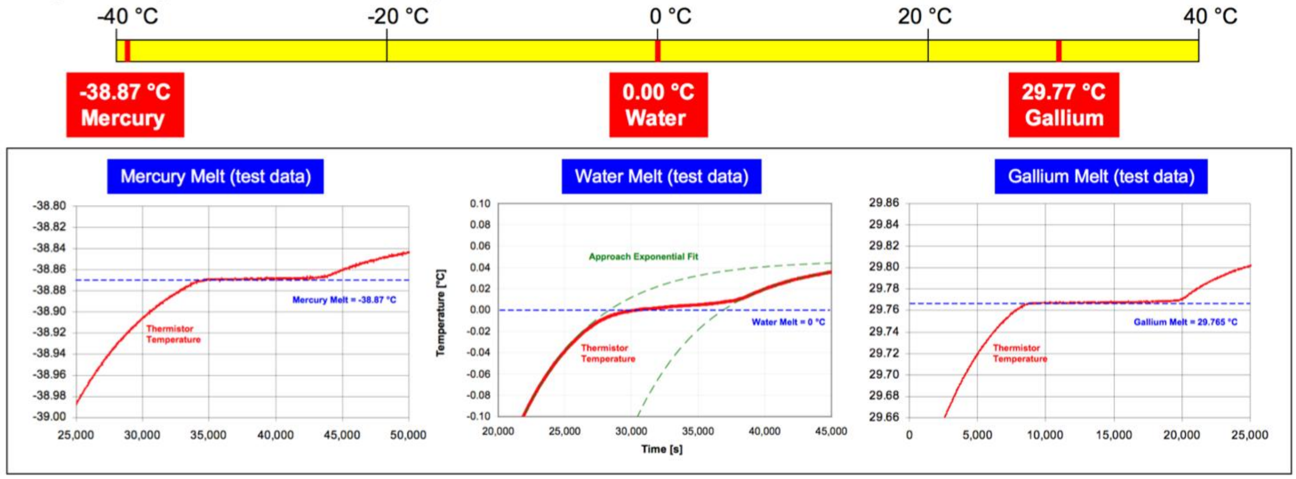

Figure 11. Melt signature test data for mercury, water, and gallium configured as illustrated in Figure 3 show that the melt plateau can be easily distinguished to within 10 mK. These three melts establish the thermistor calibration from -39 to 30 °C.

5.0 AREAS OF RESEARCH UNDER THE NASA IIP GRANT

Under the NASA IIP grant, we will concentrate on bringing this technology from component mock-up status to spaceflight readiness. Our efforts will focus on optimizing for the phase change material containment system for space flight, and verifying performance after extensive accelerated-life testing that simulates full mission lifetimes. Tests will be conducted to show that the phase change materials have not been unacceptably contaminated via dissolution, and that the containment materials are not mechanically compromised via mechanisms such as liquid metal embrittlement. Figure 12 illustrates key aspects of the system that will be investigated.

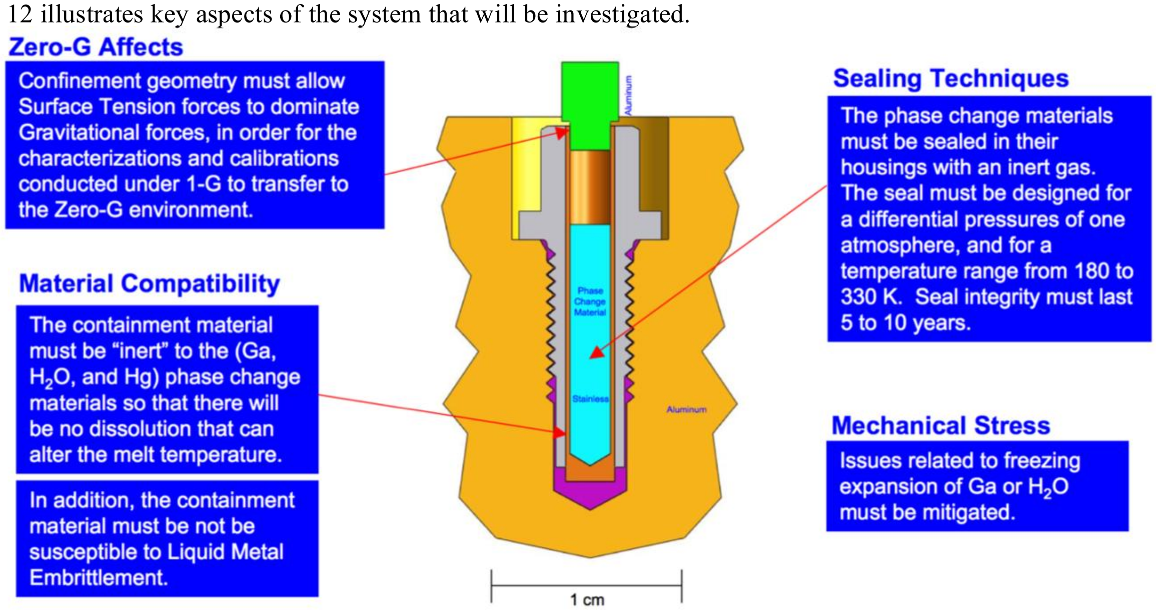

Figure 12. The major areas of research that will be addressed under the NASA IIP grant to advance this technology.

6.0 SUMMARY

The novel concept presented here for providing absolute temperature calibration on-orbit is very attractive for several reasons:

- it is extremely simple and has very low mass;
- its implementation requires straightforward modifications of an existing flight hardware design (GIFTS);
- it provides temperature calibration of all the blackbody cavity thermistor temperature sensors over a significant continuous temperature range – allowing normal blackbody operation at any temperature within this range;
- it is very accurate – each calibration point associated with a melt material can be established to well within 10 mK.

Work will be continue under a NASA IIP grant that will allow the technology to be advanced to the point where it is ready for space flight.

ACKNOWLEDGEMENTS

This work was conducted under internal research and development funding at the University of Wisconsin, Space Science and Engineering Center. Follow-on work will be conducted under a NASA Instrument Incubator Program grant.

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