

# **UW-SSEC Phase Change Cell Demonstration on the International Space Station**

**NASA Grant: NNX09AK45G**

Final Report

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## **Introduction**

This is the Final Report for NASA Grant No. NNX09AK45G (totaling \$200,000), carried out at the University of Wisconsin, Space Science and Engineering Center. This grant provided support for a flight demonstration in the microgravity environment of the International Space Station (ISS), to use multiple miniature phase change cells to provide absolute calibration of temperature sensors on-orbit - of a key technology targeted for a climate benchmark mission. The University of Wisconsin–Space Science and Engineering Center (UW-SSEC) has advanced this technology under a NASA Instrument Incubator Program (IIP-07-0006; NNX08AN35G) with Henry Revercomb as Principle Investigator. The ISS flight demonstration will add a key technical readiness milestone (beyond what will be completed under the IIP) for this technology to be used on future climate benchmark missions, including CLARREO. Benchmark measurements of absolute radiance for climate applications will hinge upon the ability to perform SI-traceable temperature calibrations on-orbit [NRC 2007, Ohring 2007, Gero 2008].

Under internal funding, UW-SSEC pioneered a novel concept that provides accurate calibration for temperature sensors over a broad temperature range, using the transient melt signatures of very small quantities of multiple reference materials [Best 2008, 2007]. This temperature calibration scheme has been integrated into the UW-developed NASA Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) flight blackbody design that includes multiple temperature sensors, and it has been demonstrated in the laboratory to absolute accuracies of better than 10 mK [Best 2006, 2005a, 2005b]. Work conducted under the IIP refined the housing design of the miniature phase change cells and verified the long-term mechanical, chemical, and metallurgical compatibility between the phase change materials and their housings.

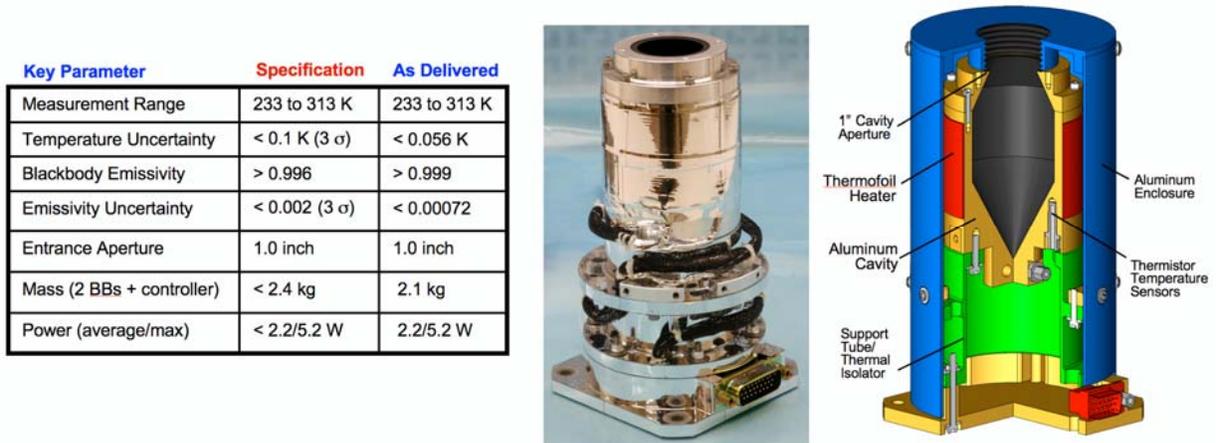
The implementation of the UW temperature calibration concept for the ISS flight demonstration makes use of an existing test capability developed by the Utah State Space Dynamics Laboratory (SDL) that provides temperature control and measurement in a package that has been previously qualified for the ISS by SDL and their Russian partners. The Temperature Reference Unit Experiment Support Package (ESP) [Bingham, 2008] was design by SDL for use on the ISS to test their concept for temperature sensor calibration. That concept uses a phase change cell containing standard reference material(s) along with the temperature sensor to be calibrated [Bingham 2007]. The SDL scheme is designed to calibrate a blackbody temperature sensor and employs a Thermo-Electric Cooler (TEC) located between the blackbody (or blackbody simulator) and the phase change cell to bring the reference materials through the appropriate melt temperature(s).

Under this grant we took delivery of an SDL Experiment Support Package (ESP) for use in the UW demonstration. This unit was thoroughly characterized and optimized (thermally and mechanically) to support our three phase change materials (water, Ga-In eutectic, and gallium). Significant work was conducted to characterize the Ga-In eutectic melt behavior, and the undercooling freeze behavior of each of the three candidate melt materials. We modified the ESP electronics board to clean up noise problems and to implement system optimizations that extended the operation to lower temperatures. We modified the software to provide continuous autonomous operation that involves cycling through the melts of our three phase change materials. Under alternate funding, we expect to deliver the system at the end of this year for a flight opportunity on the ISS. This separate funding will also support the post flight analysis.

## Background – The UW-SSEC Absolute Temperature Calibration Scheme

The novel scheme for absolute temperature calibration developed at UW-SSEC 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 multiple 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 on-board blackbody calibration system that consists of two blackbody sources and an externally located controller that provides independent temperature measurement and control for each blackbody. The table on the left of Figure 1 provides the key parameters for this system, most notably the  $3\sigma$  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 Figure 1 illustrate the blackbody design, that is scaled from the University of Wisconsin (UW) developed Atmospheric Emitted Radiance Interferometer (AERI) blackbody [Knuteson 2004, Best 2003], 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 thermfoil heater shown mounted circumferentially around the cavity cylindrical section.



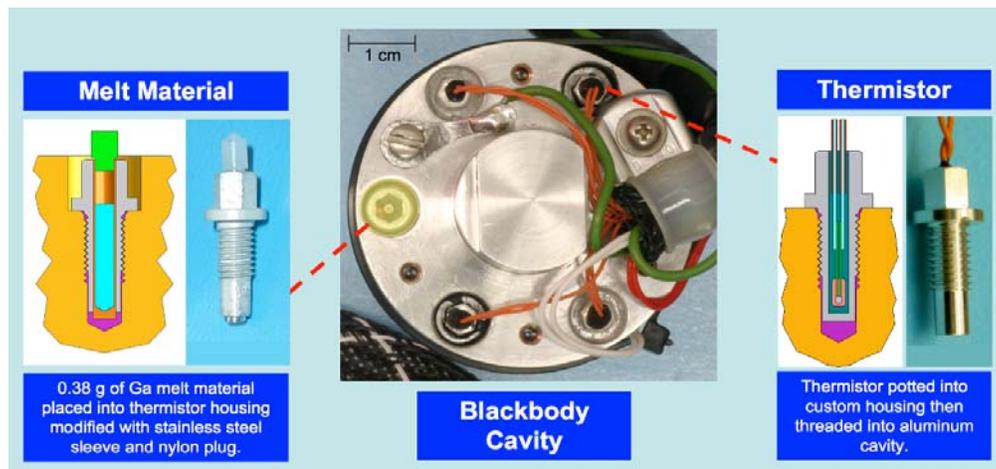
**Figure 1.** The GIFTS EDU blackbody top-level specifications and as-delivered performance are shown in table at left. A photo of the as-delivered hardware is shown in the middle without the enclosure. The cut-away figure on the right illustrates the key features of blackbody, including the thermistor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

Figure 2 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 2 illustrates the phase change material gallium; other phase

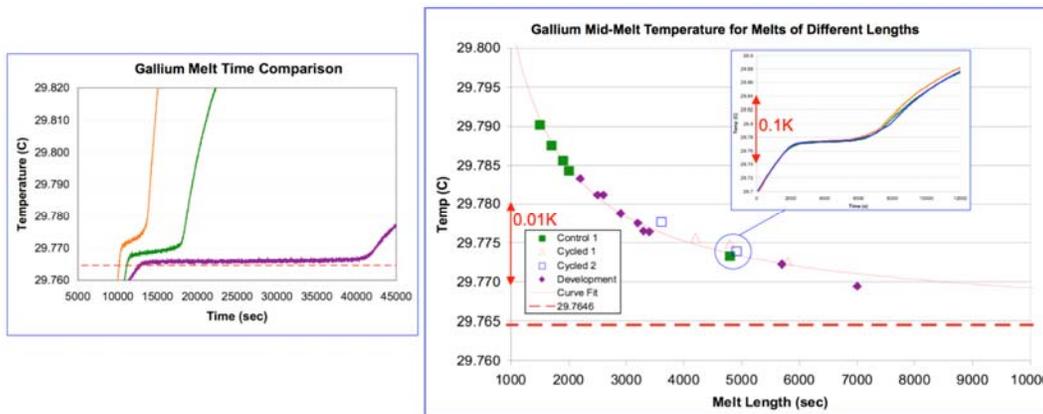
change materials are packaged similarly, and are threaded into separate locations. For example, the existing GIFTS design allows three different phase change materials to be interleaved with three different thermistors [Best 2007, 2008].

Figure 3 (left plot) shows typical transient temperature responses of one of the blackbody cavity thermistors during a gallium melts of different durations, where it can be seen that the melt plateau is clearly discernable to within 5 mK of the known melt temperature. This plot shows that as the melt times get longer the plateau more closely approaches the theoretical melt temperature. The large plot at right illustrates this by plotting mid-melt temperature vs. melt length – each data point corresponds to a single melt. This characteristic asymptotic behavior has been proven to be invariant for a given physical configuration. The inset plot at upper right shows the three melt signatures associated with the circled data points.

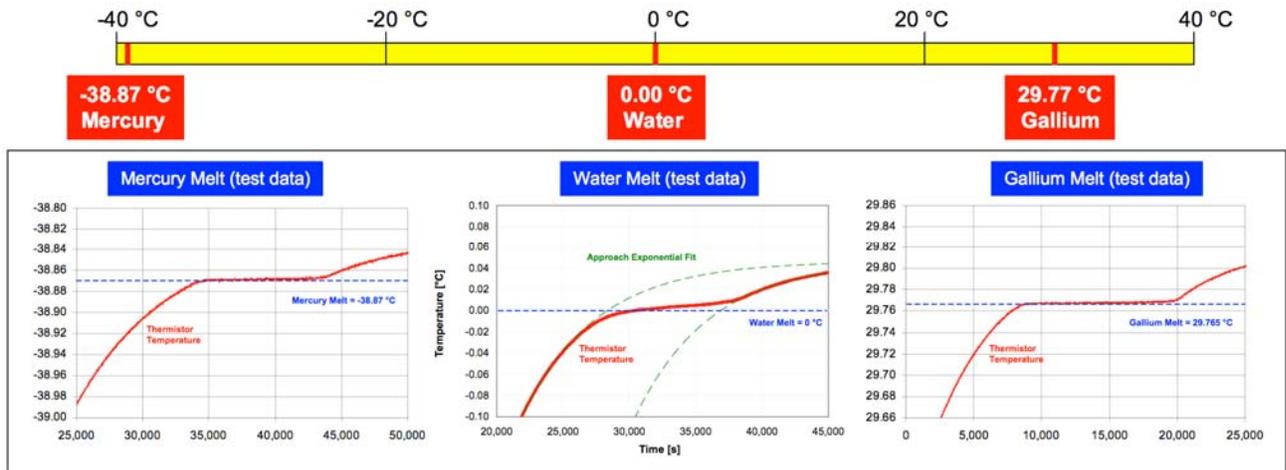
Figure 4 illustrates melt data obtained from mercury, water, and gallium to establish a temperature scale from -39 to +30 °C. For each of these melts, the phase change material was configured as is shown in Figure 2. The resulting melt plateau represents the true melt temperature within 5 mK.



**Figure 2.** 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 3.** Three transient melt signatures of different durations from a gallium phase change cell indicate that accuracies of 5 mK can be achieved (left). A characteristic curve at right can be generated from many transient signatures of different durations (right). This curve is unique to a given melt material and configuration and has been shown to be invariant over time through accelerated life testing.



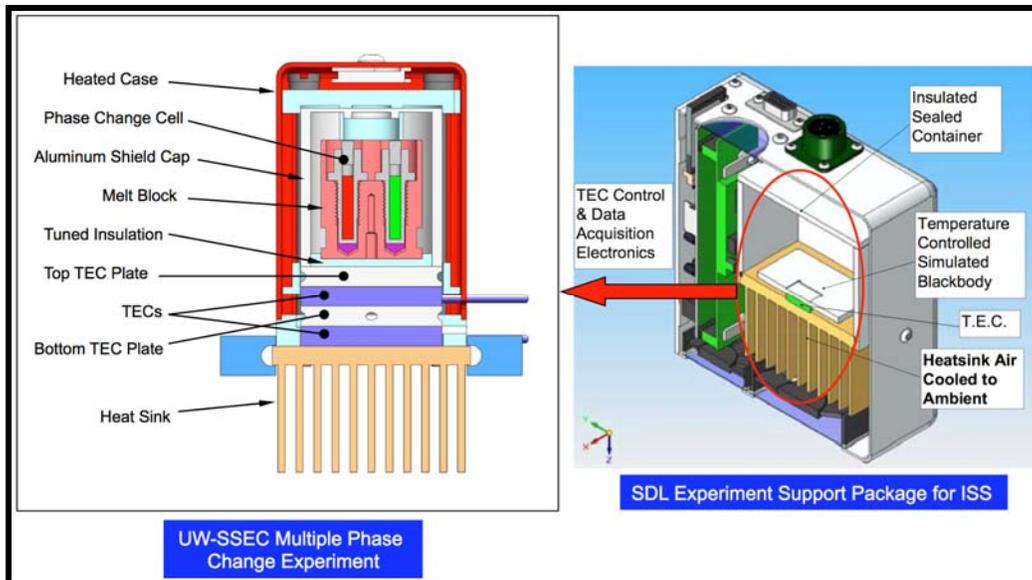
**Figure 4.** Melt signature test data for mercury, water, and gallium configured as illustrated in Figure 3 show that the melt plateau can be easily distinguished to within 5 mK. These three melts establish the thermistor calibration from -39 to 30 °C.

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

- it is extremely simple and has very low mass;
- the implementation requires straightforward modifications of an existing flight hardware design (GIFTS);
- all of the spatially distributed blackbody cavity temperature sensors are calibrated – establishing a fundamental temperature scale over a wide, continuous range, allowing normal blackbody operation at any temperature within this range;
- it is very accurate – for all the spatially distributed temperature sensors, each calibration point associated with a melt material can be established to well within 5 mK.

### UW-SSEC ISS Demonstration Configuration

Instead of testing the integrated blackbody configuration with the multiple spatially distributed temperature sensors described in the previous section, the ISS demonstration was scaled down in size and contains a single temperature sensor to be calibrated. However, the key technology being demonstrated is the transient melt signatures from the individual phase change materials in their separate housings, and this will be accomplished for gallium, water, and the eutectic alloy Ga-Sn. Figure 5 illustrates the configurations of the UW-SSEC IIS Demonstration that will be housed in the SDL Experiment Support Package.



**Figure 5.** The SDL Experiment Support Package that will house the UW-SSEC Phase Change Demonstration is shown at right. The UW-SSEC demonstration hardware is shown at left. This configuration supports three different phase change materials, including water, gallium-tin eutectic, and gallium.

### Proposed / Completed Tasks

The following tasks were proposed and carried out as part of the UW-SSEC Phase Change Cell Demonstration on the International Space Station.

- Work with SDL to understand, in detail, the interfaces (thermal, electrical, and mechanical), operational features, and constraints associated with their existing ISS-qualified Experiment Support Package. Take delivery of a ground test version of the Experiment Support Package and integrate with prototype UW Phase Change Cell Demonstration hardware.
- Optimize the UW Phase Change Cell ISS Demonstration physical configuration and test method as adapted to the SDL ISS Experiment Support Package. Of key importance is the melt signature clarity, stability, and repeatability in the presence of the expected thermal environment.
- Fabricate the final design of the UW Phase Change Cell and conduct laboratory testing and characterization tests for all the three phase change materials.

The following tasks were proposed and are yet to be conducted do to lack of a flight opportunity. It is anticipated that a flight will be available later this year. The tasks below will be conducted under separate funding, as all of this grant funding was expended to support significant unanticipated efforts to achieve the three bullets above.

- Deliver the UW-SSEC Phase Change Cell ISS Demonstration hardware to SDL and support integration and verification testing to show that the performance in the flight SDL ISS Experiment Support Package is the same as was obtained in the SSEC ground test system.
- Conduct post flight data analysis, laboratory testing, and melt characterizations at UW-SSEC. Write final report.

## Summary of Work That Was Completed

The work conducted on this project includes configuration optimizations to the as-delivered SDL Experiment Support Package (ESP), detailed design and implementation of the optimized hardware, detailed investigation

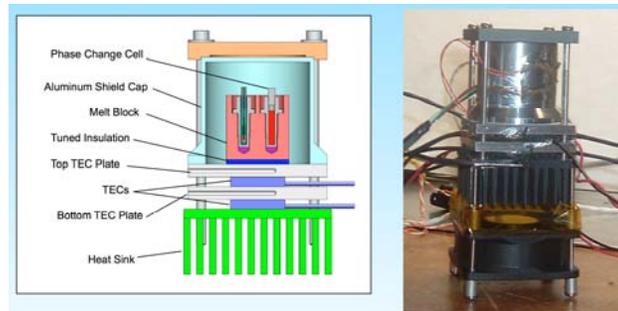
### Early Configuration Investigations

The work on this project was initially focused on identifying and optimizing the mechanical and thermal configuration of our demonstration, given the constraints of SDL ESP. The hardware from SDL was delayed from the starting time of this grant, so we experimented with different configurations in a scaled up, easy to re-configure version of the hardware. Another key focus under this grant was the investigation and characterization of Ga-In and Ga-Sn eutectic alloys with melt temperatures of 16.5 and 20.5 °C respectively. The gallium-tin was selected as the best-behaved and repeatable eutectic. This allows three different calibration melt temperatures above the SDL hardware limiting temperature of -13 °C (extended from -5 °C by UW). The calibration temperatures will be water (0 °C), Ga-Sn (20.5 °C), and gallium (29.77°C).

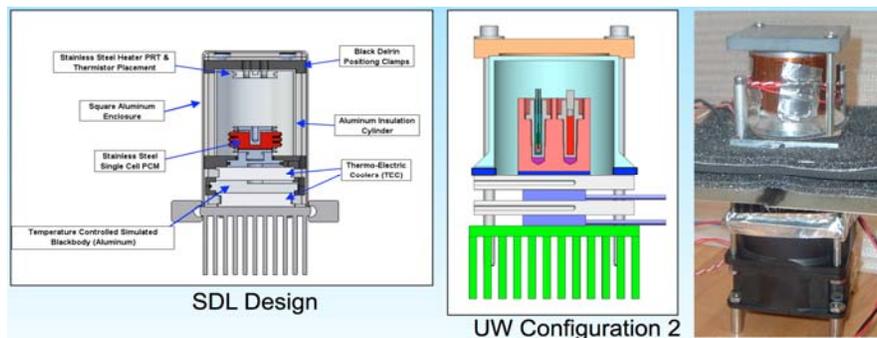
A 2x scale testbed using existing components was developed to evaluate the performance of different thermal configurations. Three shield cap coupling configurations were evaluated for minimum temperature (freeze) and melt stability performance:

1. Shield cap coupled to top TEC plate (see Figure 6).
2. Heated shield cap, which is similar to the SDL design (see Figure 7).
3. Shield cap coupled to bottom TEC plate (see Figure 8).

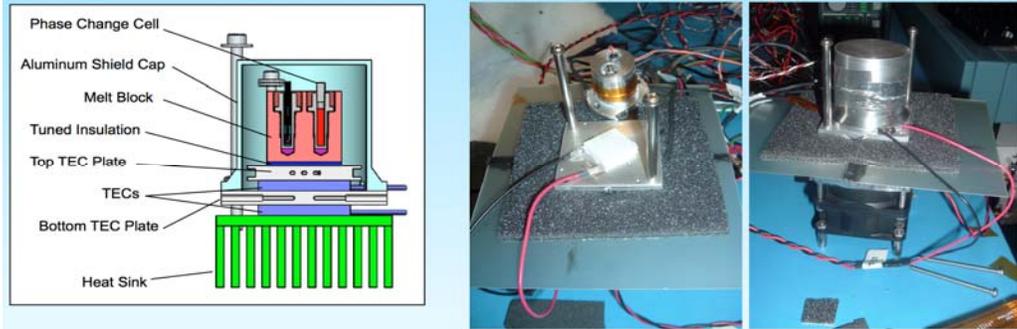
All of the configurations gave acceptable melt signatures, but the lowest temperatures were achieved by configuration 3, followed by 1 then 2.



**Figure 6.** Configuration 1: Shield Cap thermally coupled to the top TEC plate.

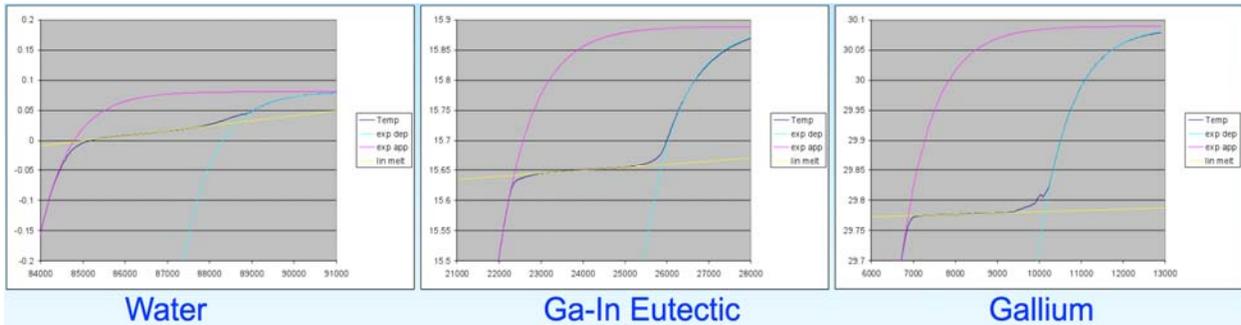


**Figure 7.** Configuration 2: Heated shield cap (similar to SDL design). This is similar to configuration 1, except that the cap is insulated from the top TEC plate and heated. Depending on the relative coupling between the TEC plate, the melt block, and shield cap, this configuration may be able to get colder than Configuration 1.

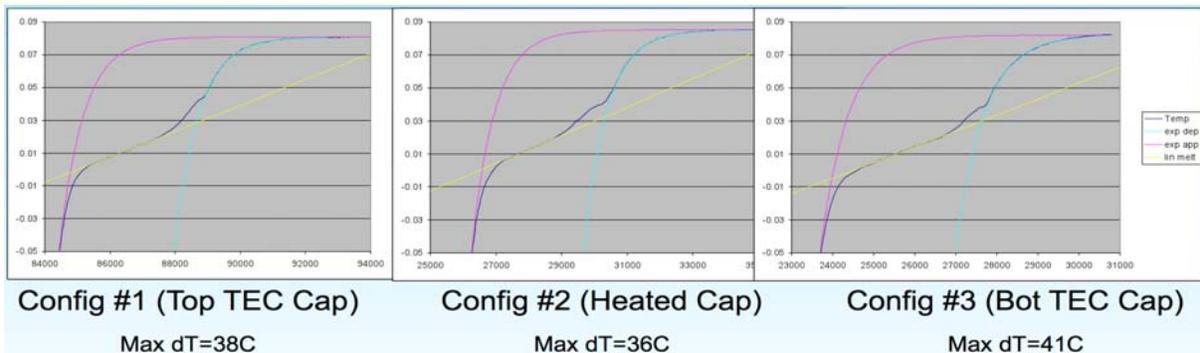


**Figure 8.** Configuration 3: Shield cap coupled to bottom TEC plate. The cooling in this configuration is more efficient. This comes at the expense of slightly less stability due to TEC ambient heat sink fluctuations.

Melt signatures were obtained using configuration 1, for each of the planned phase change materials to be used on for the ISS demonstration (water, gallium-indium eutectic, and gallium). These signatures are shown in Figure 9. The water signatures were the least distinct and more sensitive to temperature stability, so these melts were used to compare configurations (see Figure 10). For the comparison results, the “max delta” is the temperature between the melt block and ambient; configuration 3 had the best performance as indicated in Figure 10. All the signatures are acceptable, but configuration 3 shows small temperature fluctuations on the melt block after the melt, due to ambient coupling. These fluctuations were also found on the cap temperatures as well. Subsequent testing of configurations 1 and 3 with 1x scaled hardware showed that configuration 1 was superior for when considering both low temperature performance and overall temperature stability. For this reason configuration 1 was chosen as the baseline.



**Figure 9.** Melt signatures for each of the materials planned for the ISS demonstration. A very clean signature was obtained from each material.



**Figure 10.** Water signatures obtained in each of the configurations show similar quality of signatures, with configuration 3 delivering the best cooling performance.

### ***Modifications and Optimizations***

The following modifications and optimizations were made to the SDL ESP to facilitate the UW demonstration.

#### Electrical:

- It was found that the temperature sensor readings contained noise as well as drift correlated to board temperature variations. After significant diagnostic testing, corrections were made by improving the grounding and shielding improvements of the SDL board.
- During testing the ESP electronics stopped working properly. The problem was traced to a bad SensorCore board A/D converter, which was replaced.
- It was found that the 4-wire thermistor measurements were not as insensitive to lead wire resistance as they should be. This was addressed by revising test plans and recalibrating the temperature sensor.
- It was found that the TEC drivers were becoming unstable at less than rated current, which limited how cold the melt block could be driven. This was addressed by cleaning up the input and output signals on the SDL ESP board. Heat sinks were also added to the TEC transistors to prevent overheating.

#### Thermal/Mechanical:

- Revised thermal design of stack to achieve lower temperatures to ensure freezing of the phase change materials and to improve temperature stability for UW melt methodology. Key changes included: insulating the stack enclosure from the heat sink; repurposing the SDL melt heater to hold the enclosure stable; insulating the melt cell from the top TEC and adding a cover coupled to the top TEC. These changes combined with the electrical TEC driver changes reduced the low temperature limit from -5C to -13C.
- Added a vent to the experiment case, reducing the low temperature limit by an additional 1C.
- Implemented an additional phase change material (gallium-tin eutectic) to allow the validation of full on-orbit thermistor calibration within the experiment hardware temperature limits.
- Re-tuned the temperature controllers for compatibility with the new hardware.

#### Software:

- Revised software sequencing to implement UW phase change methodology, that includes autonomous operation to continually transition through three different melt materials and then go into freeze cycle.
- Implemented TEC current and temperature ramping to avoid thermal shocks to TECs and electronics.
- Validated software including error states and proper restarts after error detection.

### Final Configuration and Melt Performance

The components that make up the UW-SSEC Phase Change Cell Demonstration for the ISS are shown in Figure 11 [Pettersen 2011]. To get high-quality signatures the melt block needs to be well coupled to the double-stage TEC, yet isolated from possible thermal fluctuations in the surrounding environment. Breakout, left to right (see Figure 5 for reference): stack inside SDL ESP enclosure, heated case and TEC stack, heated case removed exposing the shield cap on the TEC, and finally the melt block on the double-stage TEC. Figure 12 shows a freeze soak followed by transitions through each of the melts, in the flight configuration. The flight demonstration will autonomously cycle through this sequence on orbit. Results obtained in the microgravity environment will then be compared with those obtained during ground testing.

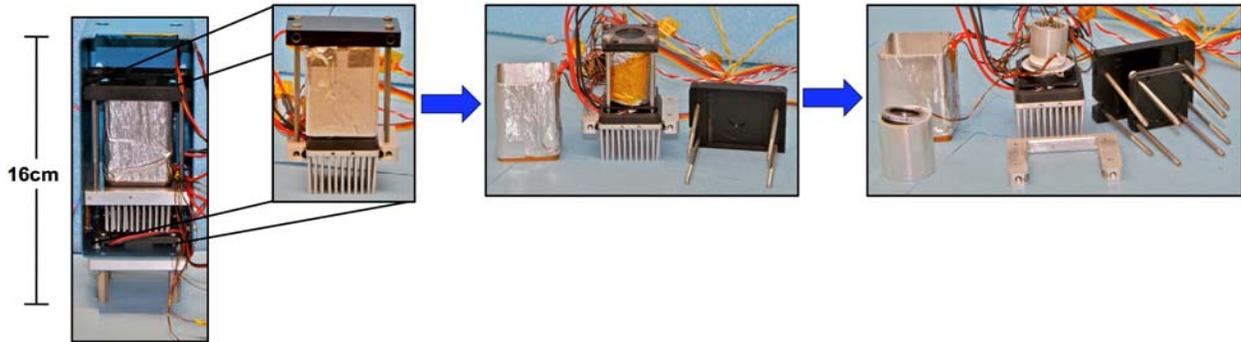


Figure 11. The components that make up the UW-SSEC Phase Change Cell Demonstration for the ISS.

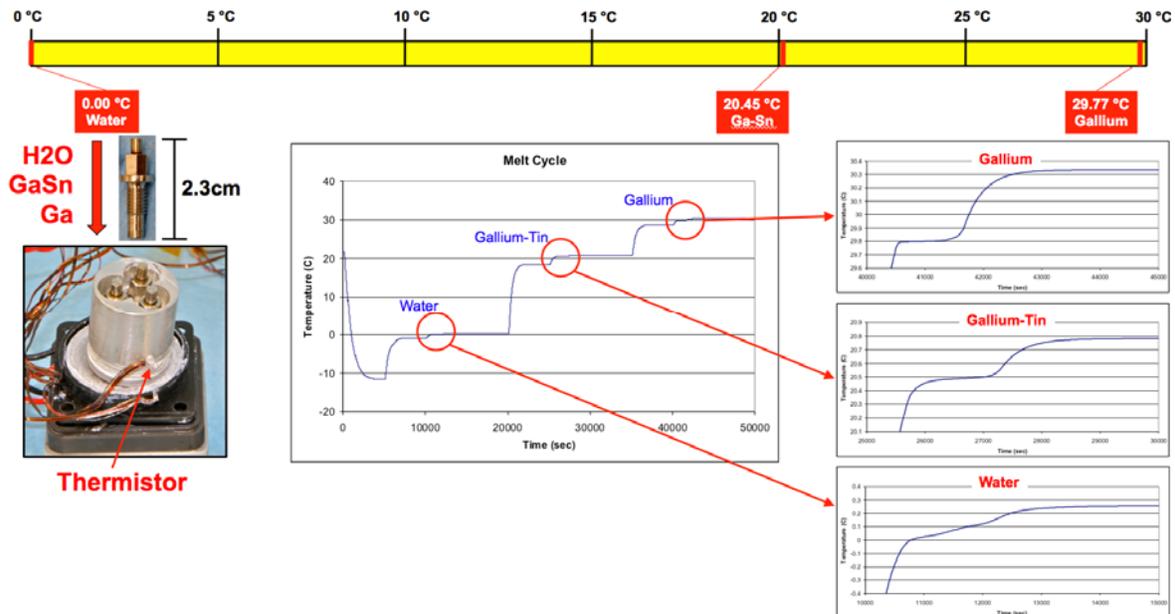
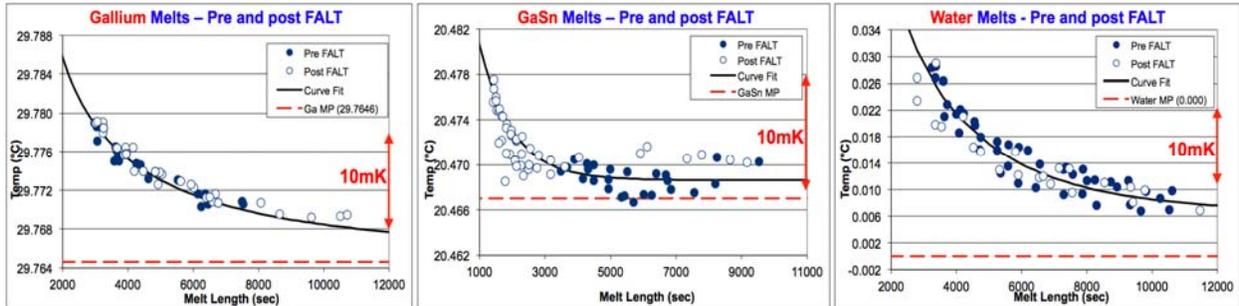


Figure 12. An example of the UW-SSEC Phase Change Cell Demonstration running through all three melts continuously – first water, then gallium-tin, then gallium. As shown at right, the melt signature is well resolved for each material to high accuracy ( $\pm 5\text{mK}$ ). While on board the ISS, the demonstration will run many sequences of melts with several different melt lengths and these will be compared to measurements obtained on the ground.

### Accelerated Life Testing

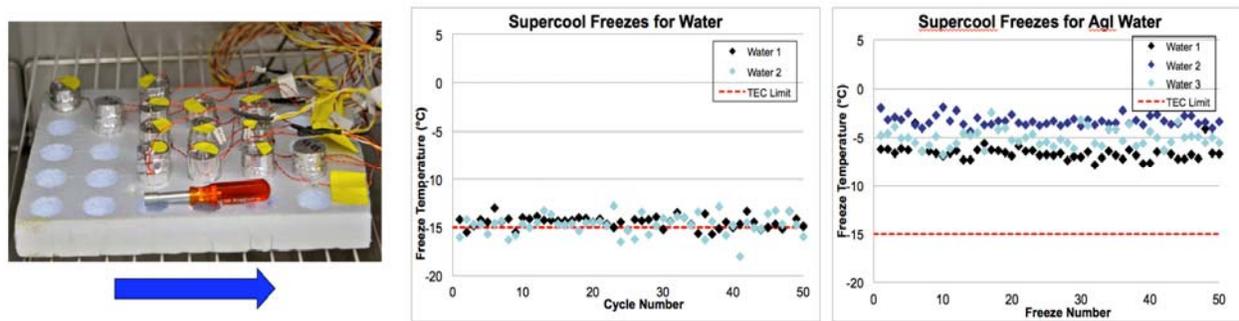
To qualify the Phase Change Cell Demonstration melt materials, a Full Accelerated Life Test (FALT) was defined that included temperature cycling as well as a hot soak for a one-year (on-orbit) material diffusion equivalence [Best 2010, Pettersen 2011]. This test is designed to stress

the housings (as all three materials expand upon freezing), as well as see any evidence of diffusion of housing materials into the melts. Signatures were gathered on several housings of Ga, Ga-Sn, and Water at many different melt lengths. After the “pre-signatures” were collected, the housings were cycled from +50C to -30C 200 times, hot-soaked at +60C for five days, and then cycled again 50 more times. Once the FALT finished, melt signatures were again run on all the housings. Figure 13 shows excellent agreement between the pre and post-signatures for all three materials.



**Figure 13.** Melt behavior displayed, both before and after accelerated life testing for gallium, gallium-tin, and water phase change cells.

The UW modified SDL ISS ESP has a low temperature limit of -13 °C – very close to the supercooled freeze temperature seen for our water phase change cells (As shown in the middle panel of Figure 14. AgI was added to the water to raise the freeze temperatures, providing a higher likelihood that all freeze attempts would be successful. AgI has very low solubility in water, thus the melt temperature is minimally altered and still well repeatable (<5mK). The freeze results from the configuration with AgI added to the water are shown in the right panel of Figure 14. The supercool freeze test configuration is shown in the left panel of Figure 14. Freezes for each of the housings were recorded by placing them in an aluminum block monitored by a thermistor and then cycled between 50°C and -30°C inside a chamber.



**Figure 14.** The supercooling test configuration is shown at left. Freeze temperatures are shown for water (middle panel) and water plus silver iodide (right panel). The results indicate that silver iodide controls the water undercooling, providing adequate margin above the experiment support package lower temperature limit of operation.

Freeze temperature testing was also conducted on gallium and the gallium-tin eutectic to verify that a freeze will occur within the system capabilities.

Another qualification of the Phase Change Cell Demonstration for the ISS was to verify that vibrations experienced during transport and launch would not affect the freeze temperature or melt signature. We obtained melt signatures on housings and cycled them from +50 °C to -30 °C 60 times to get the freeze statistics. All post vibration freezes were within the same one-degree range measured prior to vibration. The melt signatures for all three materials pre and post vibration are illustrated in Figure 16.

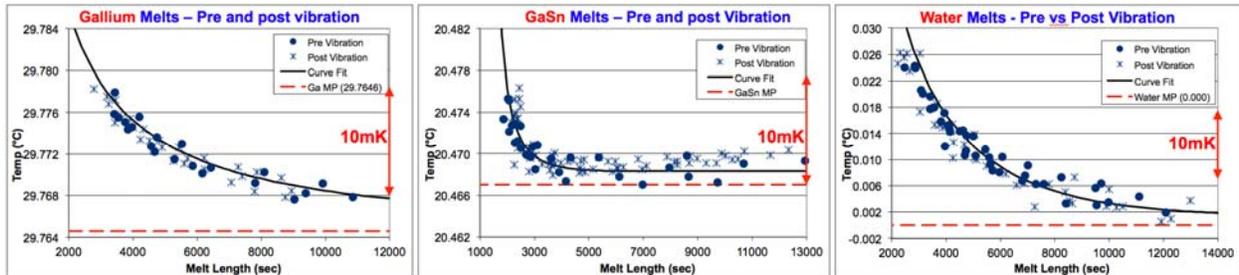


Figure 16. Melt behavior pre and post vibration for gallium, gallium-tin eutectic, and gallium.

## Summary

The UW demonstration to use multiple miniature phase change cells to provide absolute calibration of temperature sensors on-orbit has been successfully designed, integrated into an optimized SDL ESP, calibrated and tested. Phase change cells to be used for this demonstration have been fully characterized and optimized for the ISS flight conditions. An ISS flight opportunity is expected later this year. Separate funding will be used for the final flight preparations, testing, and delivery, as well as the post flight analysis.

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