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Microgravity Testing of Phase Change References on the International Space Station

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Abstract— Orbital sensors that will monitor global climate change during the next decade are exacting low drift rates from their onboard thermometry, which is unattainable currently without some means of on-orbit recalibration. Phase change materials (PCM) such as those that make up the ITS-90 are seen as the most reliable references on the ground and good candidates for orbital recalibration references.

The University of Wisconsin and Space Dynamics Laboratory have both been developing miniaturized phase change references capable of deployment on an orbital blackbody for more than six years. A critical question remains to be answered to determine their potential utility as orbital references. How, if at all, will the microgravity environment affect the phase transitions?

To answer this question, three experiments will be conducted on the international space station. Through long-time contacts at the Institute for Biomedical Problems (IBMP) in Moscow Russia, SDL has negotiated all of the flight qualification, launch and return vehicles, and crew time necessary to carry out these experiments. The experiments will test melts and freezes of three different phase change materials in various containment apparatuses.

A brief history of the development of PCM references for space implementations, descriptions of the experiment hardware, microgravity considerations for the experiments, current status of experiments, and results from pre-launch ground testing are presented.

I. INTRODUCTION

The Committee for Earth Science and Applications from Space has articulated a scientific need for orbital temperature knowledge to support infrared radiance measurements with 0.1 Kelvin uncertainty [1] over a period of at least 10 years. Onboard references utilizing phase transitions have been identified as the most likely means for realizing SI traceability for these temperature measurements in orbit.

The ITS-90 identifies several phase change materials (PCM) with reliable fixed points that can be reproduced and used as references with sub-milliKelvin absolute uncertainties for ground based calibrations [2].

Three such PCMs with fixed points in the range needed to calibrate Earth-observing sensors are gallium, water, and mercury with respective fixed points of 302.91, 273.16, and 234.29 Kelvin [2].

However, the ITS-90 description of procedures and apparatuses does not translate easily into a design for an automated orbital implementation. ITS-90 describes fixed point cells that use fragile materials to contain PCMs. They

require sensors to be placed in reentrant wells within the PCM so as to make in-situ calibrations impossible. They also require relatively large volumes of PCM to maximize stability and duration of the transition equilibrium.

Since temperature uncertainty is only one of the contributors to the desired 0.1 Kelvin uncertainty for orbital sensors, a realistic goal for an orbital implementation should be smaller to leave a margin for uncertainties added by tradeoffs to improve durability and minimize launch weight and volume. A best-effort goal of 0.01 Kelvin absolute uncertainty is currently being pursued for space-based PCM testing.

II. HISTORY

In early 2006, the suitability of various binary eutectics of gallium began to be investigated by a Russian optical and radiation calibration group called the All Russian Institute for Opto-Physical Measurements (VNIIOFI Russian acronym) in Moscow Russia under a subcontract with SDL [3]. The intended purpose of these studies was to identify suitable PCMs within the range of 273 to 303 Kelvin for use as calibration standards aboard earth observing satellites. This study was successful in identifying and characterizing several very suitable eutectics to fill the gap in the ITS-90 temperature scale between the triple point of water and the melting point of gallium.

Independent orbital studies have been conducted, which have included phase changes of various materials. These studies have shown that crystallization structures in material that solidified in the absence of gravity can differ from solids formed in 1 g [4,5]. Because the basis of these prior investigations was not temperature calibrations and repeatability of fixed-points, no accurate temperature data was recorded. The temperature of phase transitions is unlikely to be affected by gravity but there is currently a lack of evidence to support that hypothesis. PCM references need to be tested in space to characterize any possible anomalies in their behavior and to evaluate the effectiveness of design tradeoffs.

SDL has been working for the past five years with the Institute for Biomedical Problems (IBMP) in Moscow Russia to flight test several experiments on the Russian section of the International Space Station (ISS).

Working with contacts we have established over a decade of plant growth research on MIR and ISS we plan to fly at least three phase change experiments on the Russian Zvezda module of the ISS in 2011 (Fig. 1).



Figure 1. Cosmonaut Yuri Malenchenko holding SDL-built Lada greenhouse in Zvezda Module of ISS

The first two such experiments have already been fully flight qualified and delivered to IBMP for launch. The third is being completed by the University of Wisconsin (UW) and is scheduled for delivery and launch during 2011.

Orbital testing of phase changes as references will accomplish two goals: Collect data to verify the utility of phase change references in microgravity, and serve to evaluate different design tradeoffs.

III. HARDWARE DESCRIPTION

The ISS experiment package consists of two modules. A reusable power module, shown far right in Figure 2, supplies the power for all experiments. It will be launched and remain on ISS. Each experiment is housed in a separate Experiment Module, shown in the center of Figure 2. The experiment modules contain all of the electronics to perform melts and freezes. The electronics are designed around a SensorCore embedded computer manufactured by Tern Inc., far left Figure 2. They also collect temperature data to a nonvolatile memory card.

At the conclusion of an experiment the experiment module will be returned on a Soyuz capsule to deliver data collected to investigators on the ground and allow a post-flight assessment of any drift.



Figure 2. TCU Flight experiment package (center), power module (right), internal electronics (left), and a 12-inch ruler (bottom) for reference

The SensorCore is fully programmable, capable of supporting input through multiple 24-bit A/D converters, communications by two RS232 serial ports, and digital I/O. An SDL-designed interface card provides power conditioning and signal conditioning for the system.

Each experiment module houses a unique PCM cell configuration, instrumented with temperature sensors and thermal control elements. Figure 3 shows the two PCM cell configurations being tested during each of the first two flight experiments on ISS.

The configuration shown at left is a single PCM cell that uses an expandable stainless steel bellows to contain the PCM, 1 mL of gallium. The folds in the container allow for expansion of the gallium during phase transitions without causing fixed-point inaccuracies due to pressure changes. This configuration also benefits from having a reentrant well such that the temperature measurement device is completely surrounded by the PCM, yielding smaller errors due to gradients during measurements.

The configuration shown at right in Fig. 3 is a stainless steel slug with three rigid wells for containment of three different materials, ~0.75 mL of PCM each. For this flight experiment water, gallium, and a binary eutectic of gallium and tin are being tested in the wells.

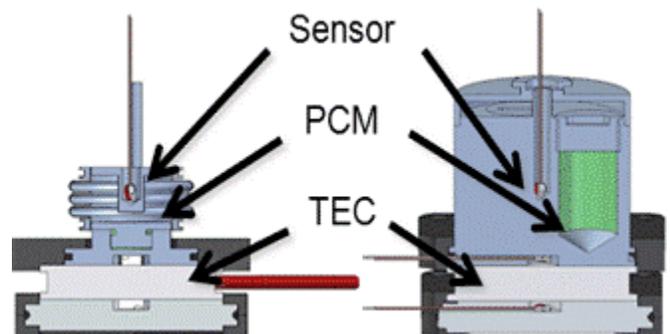


Figure 3. Two variants of PCM cells for flight testing, SDL Flight 1 (left) and Flight 2 (right), patent number US 2009/0312976 A1 pending

A central well houses a single temperature sensor to measure all three PCM temps as they melt. This configuration deals with expansion of materials by underfilling the wells. Remaining voids are controlled during filling to ensure ample compressible gas volume and minimize pressure changes within the cell due to PCM volume changes during phase transitions. The void volumes are calculated to maintaining pressures within the cell constant to within ± 0.25 atmospheres. This translates to approximately 0.0025 degree error for water whose transition temperature varies by approximately 0.01 degrees Celsius between zero and one atmosphere [2].

Both cells are constructed from stainless steel to avoid PCM contamination. Laser welding produces a hermetic container with no moving seals minimizing the chance of a container breach. Both cells can be heated and cooled approximately ± 30 degrees Celsius from cabin temperature with a 15-Watt Peltier thermo-electric cooler. Each cell occupies approximately one cubic inch inside the experiment module housing.

IV. PRELAUNCH TEST RESULTS

An array of testing was performed on the flight units before delivery per Russian protocols to verify safety, compatibility, and survivability requirements for space travel were met. Assurance of ability to meet scientific objectives was verified as part of this prelaunch testing.

During the software and algorithm development several melts were performed in the experiment hardware to identify values for controlled parameters that affect the melt data collection such as temperature set points and software thresholds. Data collected during these melts helped to characterize the cells and establish realistic repeatability and accuracy expectations for the flight experiments.

A final preflight experiment simulation was performed in which each flight unit was powered up and left running for approximately one week to perform melts automatically as it will on the ISS. The following plots are a summary of the flight simulation for the Flight 1 hardware, and selected melt data collected in the Flight 2 unit during the software algorithm development testing. Both are representative of data expected from the ISS testing.

Figure 4 shows the PCM temperature readings from several gallium melts collected during the Flight 1 experiment simulation. The ambient temperature conditions to which the hardware was exposed during this test are similar to ambient conditions observed on ISS during SDL plant biology experiments, namely average temperatures varying between 22° and 25° Celsius.

The ambient temperature was shown to affect the melt temperatures slightly but the repeatability from one plateau to the next even under varying ambient conditions was better than 0.005 degrees. The melt plateaus show about a 0.01 degree rise during the phase transition with an initial inflection point at ~ 29.75 degrees Celsius. The gallium melt temperature is 0.01 degrees higher at 29.76 degrees Celsius. That is within the ± 0.03 degree absolute uncertainty of the temperature

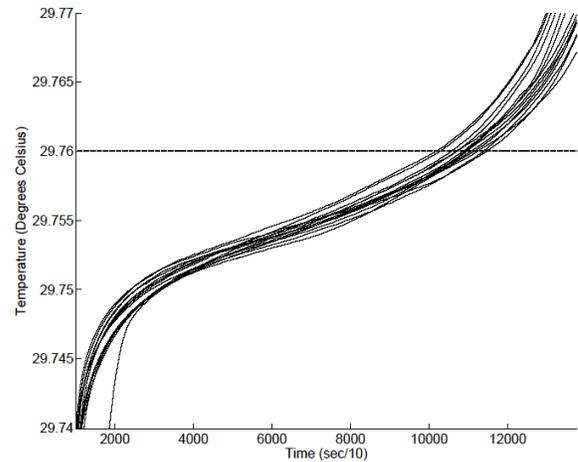


Figure 4. Preflight temperature data from several melts of Ga in MOTR Flight 1 experiment hardware

sensor calibrations. The lines on the plot show smoothed data, averaged to reduce instantaneous electrical noise in the readings.

Fig. 5 is a plot of some initial data collected with the Flight 2 hardware during gallium melts for characterization and software algorithm development. The three melts shown are displayed as original unsmoothed data in black and smoothed data in grey.

Flight 2 gallium melts again exhibited better than 0.005 degrees repeatability but because the cell geometry is different, the melts showed more temperature rise during the phase transition, indicative of thermal gradients in the container affecting the measurement. This is to be expected when considering the fact that the PCM temperature sensor in the Flight 2 configuration is in contact with the PCMs through the container rather than a reentrant well as with the Flight 1 cell configuration. All the melts took place within ± 0.02 degrees of the recognized gallium melt temperature.

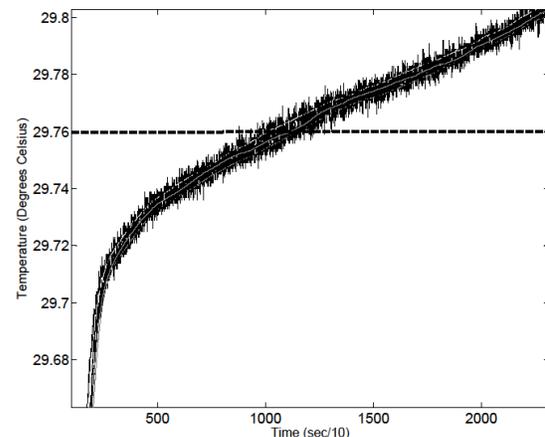


Figure 5. Preflight temperature data from three melts of Ga in MOTR Flight 2 experiment hardware

Figure 6 shows preliminary data collected with the Flight 2 hardware during three gallium-tin eutectic melts for characterization and software algorithm development. The three melts shown are displayed as original unsmoothed data in black and smoothed data in grey.

Melt times and temperature rises during each phase transition for gallium-tin were similar to those of gallium alone. The PCM temperature measurements rose ~ 0.08 degrees over approximately 30 minutes.

The absolute accuracy of the eutectic melt data is difficult to quantify because the gallium-tin melt temperature is not known with the same certainty as gallium. Test results obtained for SDL by VNIIOFI showed that gallium-tin eutectics melted between 20.47 and 20.5 degrees Celsius and that the constituency of the materials can affect the melt temperature [3]. The trials shown resulted in melt temperatures within 0.05 degrees of this range.

Gallium-tin melts collected in the Flight 2 hardware were very repeatable. Consecutive melts for gallium and its eutectics are more repeatable after an initial conditioning melt. The first melt in a series tends to yield less characteristic temperatures as the material is being brought into order. Subsequent melts are more uniform. Fig. 6 shows one initial conditioning melt approximately 0.01 degrees higher than the other two subsequent melts. Subsequent melts of gallium-tin were repeatable to better than 0.005 degrees as other data shown.

Water is the third PCM being investigated in the second flight unit. No water data is shown here. In general the water data was less repeatable than gallium and eutectics data and is not expected to yield favorable results from the flight experiments. The experiments with water will still be conducted on ISS to glean what information is obtainable from them.

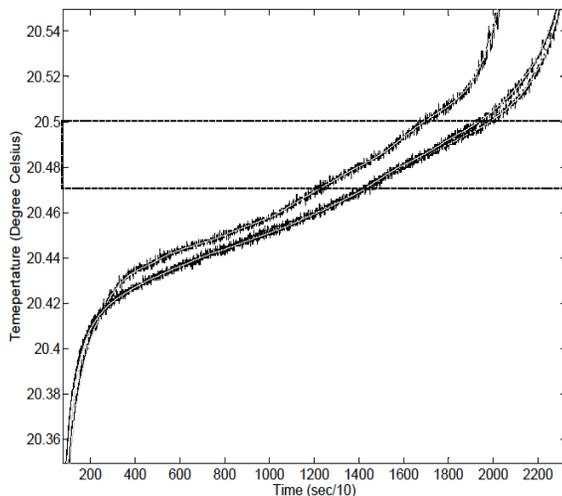


Figure 6. Preflight temperature data from three melts of GaSn in MOTR Flight 2 experiment hardware

V. CURRENT STATUS OF EXPERIMENTS

The flight experiment design is complete. An initial flight qualification unit was used to demonstrate compliance with all of the Russian flight requirements. Two flight units with experiment cells as described in the previous section were delivered to IBMP in Moscow Russia on December 8, 2010 for the first flight unit and on February 25, 2011 for the second. A photo of the first flight experiment and power module is shown in Fig. 7 in the shipping container as it was delivered for launch.

All of the delivery acceptance tests were completed successfully. These two units are currently waiting for the formal approval from the Kazan Scientific Center (KNTS Russian acronym) of the Russian Academy of Science. Formal meetings have been held between IBMP and KNTS. Several KNTS concerns about the experiment and data sharing were addressed to KNTS representatives' satisfaction. The formal written approval from KNTS, needed to manifest the MOTR experiments for launch to ISS and complete the Russian Space Agency flight acceptance testing, is reported by IBMP to be forthcoming. IBMP is currently doing everything within their power to speed the process along.

Current plans are being made to launch both of these experiments in late 2011.

A third experiment housing a University of Wisconsin designed and built cell is currently being constructed and tested. This third experiment is being completed on a schedule to allow a launch at the same time as the previous two experiments in 2011.

All experiments will be returned to earth on the next available Soyuz capsule. Data will be recovered after landing and ground testing will be repeated to see if any noticeable drift occurred in the hardware that may affect the interpretation of the data collected on ISS.



Figure 7. MOTR Flight 1 experiment as delivered to IBMP Moscow

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