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Verification Testing of a Helium Gas-Gap Heat-Switch Controlled Calibration Target

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The Meteosat series of spacecraft are meteorological satellites, providing data that inform weather forecasts across Europe. Meteosat Third Generation (MTG) is expected to allow data to be collected into the 2030s. The Flexible Combined Imager (FCI) and Infrared Sounder (IRS) instruments will be flying on the MTG spacecraft. The ground based calibration targets used to calibrate these instruments are being designed at the Science and Technology Facilities Council's Rutherford Appleton Laboratory Space Department (STFC RAL Space). They are designed to operate in vacuum over a temperature range from 160 K to 370 K, with an additional capability to operate at ~100 K as a point of near-zero radiance. The overall blackbody design is based upon a helium gas-gap heat switch, which reduces the total power budget and allows operation over the entire range. A Breadboard Model (BBM) was designed and built as part of the verification process. The testing of the BBM took place at STFC RAL Space between November 2015 and March 2016, and during August 2016. Overall, the testing demonstrated that a helium gas-gap can be used to successfully control over the entire temperature range desired, meeting both temperature uniformity and stability requirements essential to achieving the instrument calibrations. This paper will present the lessons learnt and the solutions implemented following these series of tests. In particular, it will focus upon the complications associated with the use of helium gas as the heat-switch: sealing the helium into the gas-gap, controlling the pressure of the helium accurately, induced arcing across the connectors due to helium breakdown, and steps required to mitigate these effects.

Nomenclature

AC	=	alternating current
BBM	=	Breadboard Model
ESA	=	European Space Agency
FCI	=	Flexible Combined Imager
He	=	Helium
IRS	=	Infrared Sounder
LN_2	=	liquid nitrogen
MTG	=	Meteosat Third Generation
OGSE	=	operational ground support equipment
OHB	=	OHB Systems AG
PID	=	proportional, integral, differential control
RAL	=	Rutherford Appleton Laboratory

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STC	=	Space Test Chamber
STFC	=	Science and Technology Facilities Council
TAS-F	=	Thales Alenia Space - France

I. Introduction

Both the Flexible Combined Imager (FCI) and Infrared Sounder (IRS) are instruments which will be flying on the Meteosat Third Generation (MTG) satellites. The on-ground calibration of these instruments will be performed prior to integration on the spacecraft using the blackbody calibration targets being designed and built by RAL Space in Oxfordshire, UK.

A blackbody calibration target usually comprises a target plate, surrounded by a baffle that an instrument views. The absolute temperature and gradients within the target must be known and controlled. In addition, the emissivity of the cavity must be known. This is to ensure that the target provides a known radiance source to the instrument with quantified uncertainties that are small enough to enable test and calibration of the FCI and IRS.

Melzack et al (Ref 1) describes the detailed design of the blackbodies under development, highlighting several key design features and performances. In summary, as shown in Figure 1, the blackbodies consist of three concentric cylinders:

1. An outer liquid nitrogen (LN_2) jacket to provide the cold boundary temperature. This is fabricated of stainless steel.
2. An aluminium inner cavity, the inner surface of which is painted with Mankiewicz Nextal-Velvet-Coating 811-21 which is the radiating surface for calibration purposes.
3. An aluminium radiation shield, which sits in the helium (He) space between the LN_2 jacket and the inner cavity.

The baseplate diameter is 432 mm and the length of the baffle is 1 m. Overall a blackbody has a mass of 200 kg. The He space allows the blackbodies to be operated as a variable-thermal-conductance gas-gap heat switch. With varying pressures of He in the space, the thermal conductance between the cavity and the LN_2 is varied, allowing temperatures from 78-370 K to be achieved at the radiating surface. Table 1 summarises the key performance features.

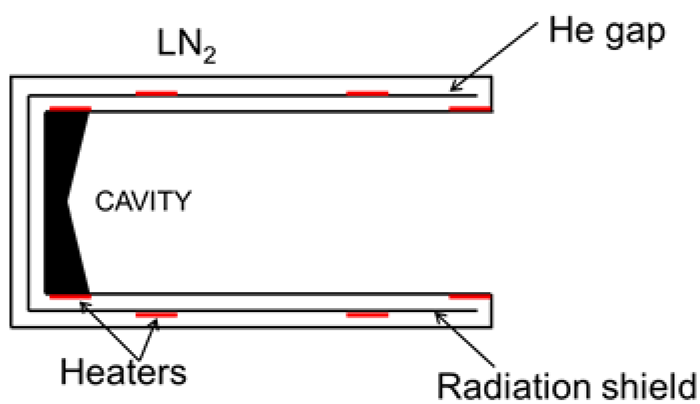

Figure 1. Diagram showing blackbody layout.

Table 1 Key performance features of blackbody.

Parameter	Value	Comment
Temperature range	78-370 K	Lowest controlled temperature is 92 K, however 78 K is achievable at the radiating surface
Thermal stability	1 mK/hour	As achieved during BBM testing
Thermal uniformity	<300 mK maximum dT over 432 mm diameter baseplate	As inferred from BBM testing
Helium pressure set points	10^{-4} mbar (340-370 K) 0.025 mbar (175-340 K) 900 mbar (78-175 K)	Temperature ranges at each set point given due to power limit of 3 kW

II. Prototype Testing – Experimental Set-up

The breadboard model (BBM) is a full scale prototype of the calibration targets, and was tested in the Science and Technology Facilities Council (STFC) Rutherford Appleton Laboratory Space department (RAL Space)'s 3 m Space Test Chamber (STC) between December 2015 and March 2016 (phase 1 testing) in order to confirm several key thermal performance characteristics (gradients and stability) as well as to derisk several key engineering design concepts (He heat switch). A second phase of testing (phase 2 testing) took place during August 2016 in order to optimize the control system as well as test several further engineering changes. Assembly of the BBM is shown in Figure 2.

As detailed in Melzack et al (Ref 1), overall the BBM performed as expected: the gas-gap heat switch concept was proven a success, with both stability and uniformity requirements being met across the broad range of temperatures demanded of the calibration targets. In the following sections, the key lessons learnt are discussed along with the solutions implemented. In particular, the practical application of the thermal control system proved the most challenging, which will be discussed in detail.

Figure 2 Assembly of BBM at RAL Space. *Heaters are clearly displayed on both the black coated inner cavity and the aluminum radiation shield.*

III. Helium Arcing – Voltage, Pin Spacing and Pressure

Paschen's law describes the conditions necessary to cause electric arcing between two electrodes in a gas. Arcing onset is dependent upon the gas pressure, the spacing between electrodes, and the voltage through the electrodes. The connectors used to wire up the heaters and temperature sensors in the calibration targets are in the helium space, and so helium arcing is a risk.

The pin spacing in the connectors is comparable to the spacing between electrodes, and was chosen in order to accommodate the required connections given the size of the flanges available. The voltage (240 V AC) into the heaters was fixed throughout the testing. The helium pressure, however, varies from 0 to 900 mbar during operation. The pressure set points used (10^{-4} mbar, 0.025 mbar and 900 mbar) do not cause helium arcing given the voltage and pin spacing used.

However, breakdown readily occurs between 8 and 30 mbar at 240 V AC at the pin spacing necessary in the connectors. When transitioning between helium set points, these pressures will be seen in the helium gap, if only temporarily. If the heaters are switched on during this period, then arcing will occur. Evidence of this phenomenon was seen in January 2016, with one set of connectors burning out due to helium arcing, halting operations.

In order to avoid such arcing, a typical solution is to pot connectors in order to isolate the pins from the helium. However, the effectiveness of this is procedure-based, and is highly dependent upon the quality of the potting. Whilst regular product assurance procedures apply to potted connectors prior to integration into the calibration targets, any other electrical faults in the helium gap (such as nicked wires or solder) would also trigger arcing, which from a quality assurance perspective would be almost impossible to fully capture. Alternatively, lowering the operational voltage into a regime for which helium breakdown cannot occur at any partial pressure offers a robust workaround to assure no arcing can occur: both the Paschen curve and supplementary tests carried out at RAL Space show arcing not to occur below 156 V AC. Thus, the operating voltage was dropped from 240V AC to 110V AC, which makes the system inherently safe from helium breakdown.

Dropping the voltage adds complexity into electronic support equipment, as a step-down transformer is needed in order to allow the blackbodies to still be run through mains power.

IV. Helium Seal – Interface and Leaking

As described in Ref 1 (Melzack et al), the mismatch of thermal expansion at the front of the blackbodies led to the use of a Technetics HELICOFLEX® seal to seal the He gas gap between the LN_2 jacket and the inner cavity. During the first phase of BBM testing, although a seal had been leak-tested prior to incorporation into the prototype, there was evidence of helium leaking into the STC at a higher rate than specified. The leak rate seen (10^{-5} mbarL/s) was not enough to affect the BBM's performance, nor was it too much for the turbo- and cryo-pumps in the STC to clear, but the leak was several orders of magnitude larger than specified by the manufacturer (10^{-9} mbar L/s).

Upon investigating both the seal and the flanges, small dents were found on the seal (see Figure 3), and the surface roughness of the flanges was smoother than specified. A test dummy piece manufactured to correct surface characteristics, with stringent quality control both on the flange surfaces and the accepted seal mating faces, subsequently was able to seal to specification in ambient conditions.

However, further testing of the dummy flanges in vacuum conditions revealed worst-case leak rates of 10^{-5} mbar L/s at ~100 K, and leak rates between 10^{-9} and 10^{-6} mbar L/s at higher temperatures as well as during temperature transitions. There are a number of possible causes (bolt stretch, spring washer flattening, shear of sealing face) which are still undergoing investigation, as well as mitigating procedures for creeping the seal (e.g. a pseudo-annealing bake). It should be noted that the performance of the blackbodies is unaffected with leak rates up to 10^{-4} mbar L/s.

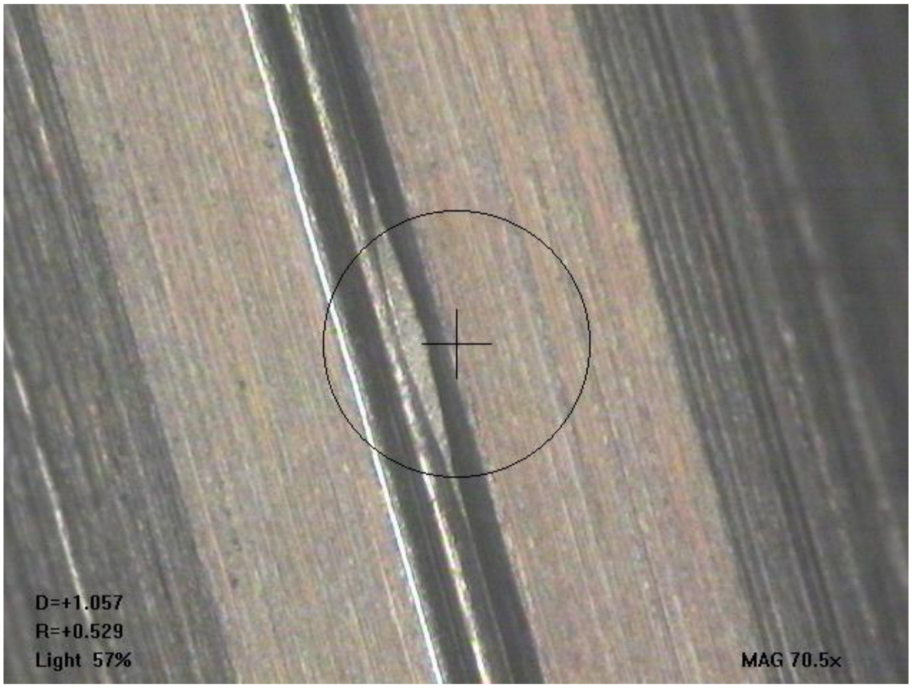

Figure 3 Magnified view of helium seal. *There is a clear marquise shaped dent on the knife edge part of the seal. This is a leak path for the helium. Many similar dents were found around the circumference of the seal under microscopic inspection, however they were not noticed with the initial visual inspection.*

V. Helium Pressure Control

The intermediate pressure of helium required in the heat switch gap is 0.025 mbar; being able to maintain this very low pressure precisely and accurately is important to ensure there is a consistent gas conductance. The system used will need to control the helium, and needs to be responsive enough to compensate for any leakage or variations in pressure due to changes in temperature.

In the August 2016 test campaign, an automated helium control system was used. For phase 1 testing however, a manual set-up of valves and gauges was developed in order to achieve the required helium pressures, allowing the rate of adding (or removing) helium from the system to be investigated. Too fast an introduction of helium led to LN_2 being exhausted from the jacket, as the heat from the calibration target transferred into the LN_2 jacket too quickly, wasting nitrogen, and caused a non-uniform boundary temperature in the jacket, while the liquid nitrogen replenished.

The initial rapid change from 0.025-1 mbar saw the most LN_2 being exhausted (during the transition from 0.025 mbar to 900 mbar). This correlates to the rapid increase in thermal conductivity seen for helium pressures up to about 1 mbar. The optimized manner in which to introduce the helium for this transition is found to be 30 minutes for the initial 0.025-1 mbar change, and a further 30 minutes between 1-900 mbar. However, with the introduction of the automated system, more rates of change can be trialled and the most time (and nitrogen) efficient option will be implemented in the final design.

VI. LN_2 Exhaust

As heat from the calibration target is transferred through the helium gas gap (and any other thermal leak paths) into the LN_2 jacket, the liquid nitrogen will boil and release nitrogen gas. The design of the jacket is such that as nitrogen gas boils out the exhaust, liquid nitrogen from a gravity-fed phase separator will replenish what was lost from the jacket, maintaining the boundary temperature – and hence maintaining the stability of the blackbody baseplate temperature without perturbation.

During the phase 1 testing, it was noted that at the 160 K set point, the nitrogen was boiling faster than it could be exhausted out the jacket, resulting in a build-up of gas in the LN_2 jacket. This issue was diagnosed based on the non-uniform temperatures being read-out by the thermocouples placed on the jacket. Those at the top of the jacket were about 40 K warmer than the 80 K being read from the bottom of the jacket (where there was still liquid). This temperature set-point used nearly the maximum amount of power from the heaters at the intermediate (0.025 mbar) helium pressure, resulting in more heat than predicted being transferred into the nitrogen. This created a non-uniform boundary from which a uniform radiating surface of the calibration targets cannot be reached.

To mitigate against this high-power case, the exhaust port was resized from ¾'' (19 mm) to approximately 2" (51 mm) diameter: in the August 2016 testing with this larger diameter exhaust, liquid was maintained in the jacket at all times, allowing all temperatures to be achieved by the calibration targets at the expected uniformity.

VII. Control System Optimization

The calibration scientist struggles between exorbitant chamber costs (which drive the need to shorten calibration durations, as usually emphasised in the transition times between calibration temperatures) and the need to have highly uniform and stable calibration targets (to provide the best calibration possible); the two, however, are in direct contradiction with each other. The design developed here favours uniformity and stability, with a high mass baseplate ensuring the design is inherently able to meet these technical radiometric requirements. However, this comes at the expense of the rate at which the system is able to transition between one temperature and the next, and to stabilise to that new temperature: the time constant of the system is around 20 minutes. Designing a control system for blackbodies is a complicated process, needing to optimize both the technical and logistical viewpoints.

A. Control System Hardware and Initial Set-up

The cross-sectional diagram in Figure 1 shows the locations of the four main heating rings on the BBM (and the final design). There are two heater bands on the cavity itself, one by the cavity base and one on the aperture end of the cavity baffle. There are an additional two heater bands on the radiation shield. These heaters are controlled by Eurotherm 2704 units, but can also be controlled manually, as they were for parts of the BBM testing.

The BBM had a total of 29 temperature sensors, the majority of which were used for monitoring the temperature gradients and thus the uniformity of the blackbody. These sensors' outputs during the tests were also used to inform the correlation of the thermal model. Four of the 29 temperature sensors were wired into Eurotherm control units, and these form the basis of the temperature control for the blackbody. The remaining monitoring sensors were outputting into an Isotech MicroK 500 unit. For the final design, there will be a total of four control sensors, and an additional seven sensors to monitor the uniformity of the radiating surface.

There are two key operating modes for the blackbody: steady state operation and temperature transitions. During steady state operation the blackbody will maintain the set temperature at the radiating surface so that measurements can be taken. The temperature transition mode will be used when moving from one temperature set-point to another. The control philosophy for both operating modes is still being refined; the lessons learnt and progress made so far is presented below.

B. Phase 1 Testing

In steady state mode, the system is PID controlled to allow for the necessary stability and uniformity to conduct measurements. The design is inherently stable and uniform, with a high thermal mass. Three of the four heater bands are active during steady state operation. Both bands on the radiation shield are controlled with a single PID loop, to maintain a uniform temperature that is conducted through the gas (or radiated through the vacuum) to the inner cavity. The band of heaters on the cavity baffle near the aperture are also PID controlled in a separate loop to maintain the correct temperature and control gradients along the baffle.

During phase 1, when in steady state operation, the system indirectly controlled the baseplate through conduction and radiation. This was achieved through active control of the radiation shield and cavity baffle. The radiation shield was controlled from a temperature sensor placed on the radiation shield itself, close to a heater. This allowed the accurate control of the radiation shield temperature rather than the accurate control of the baseplate. To achieve the necessary baseplate temperature, an offset between the radiation shield and radiating surface temperature needed to be well known. Figure 4 shows the control strategy schematically. This offset was derived through a mix of high fidelity modelling and testing. Since the baseplate was not directly controlled, the response was slow and hence could not negate the natural tendency of the system to drift. This was seen during a 24 hour soak at 288 K. During the 24 hours, although the temperature of the radiating surface only drifted by 0.16 K, it was clearly not under active PID control, as can be seen in Figure 5 .

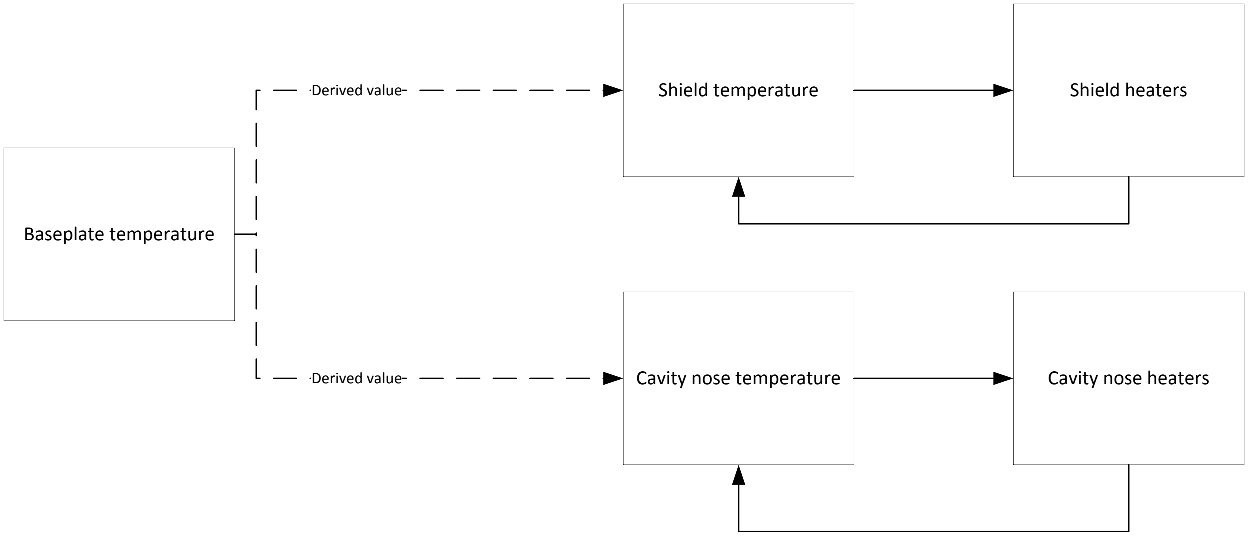

Figure 4 Phase 1 steady state control strategy.

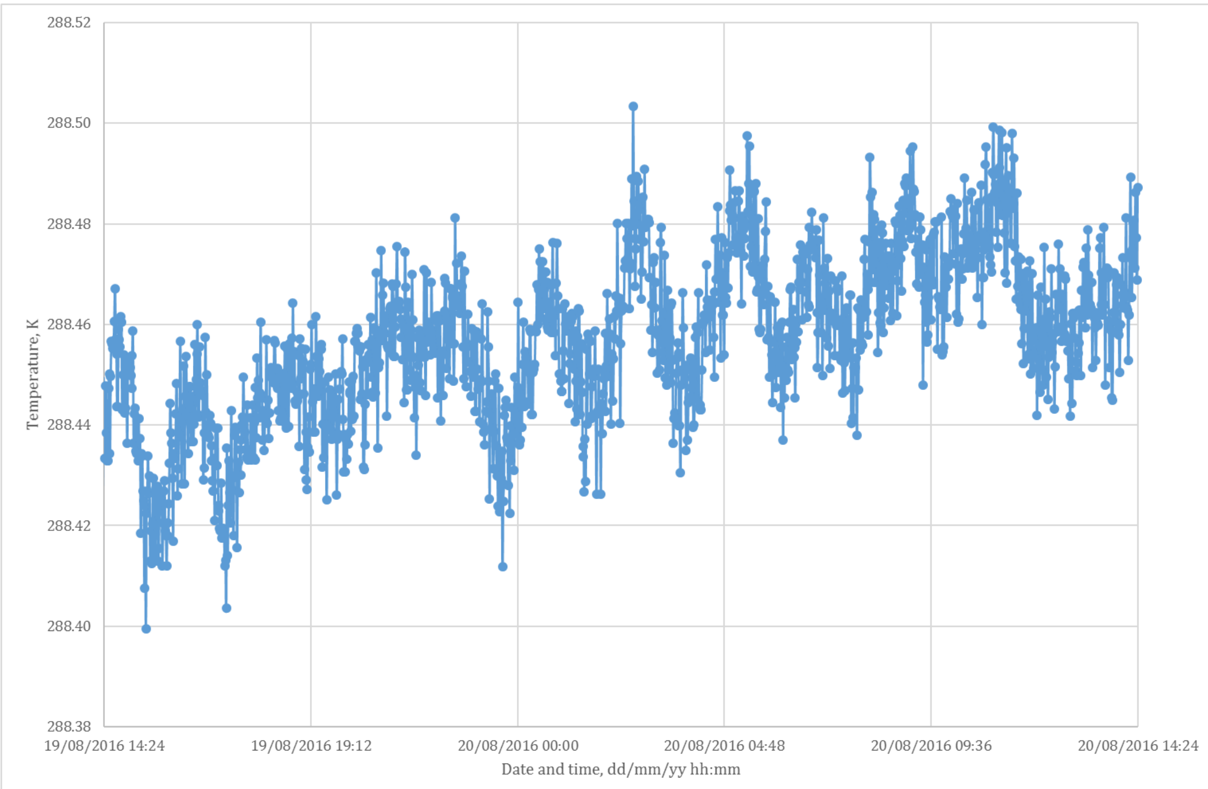

Figure 5. Temperature of radiating surface during 24 hour soak.

The transition mode is used for larger temperature changes and relies on algorithms and set instruction from the software rather than PID control. For a large temperature increase, the software used a boost mode which activated heaters around the cavity baseplate and cavity baffle. The baseplate heaters moved the temperature quickly but could not be used in steady state mode due to the stringent uniformity requirements. Once within a set dT of the temperature set point, the system would revert to the steady state control mode to finalise the temperature move. To minimise the over-temperature of the cavity baffle, the cavity baffle sensor was used as the switch between transition and steady state mode. The cavity baffle is 5 mm thick, compared to the cavity base which is 50 mm thick. The baffle therefore reached the required temperature set point much faster than the base; switching the system to steady state mode prematurely (see Figure 6). This premature switch required the baseplate to do a large temperature transition under steady state PID mode, not utilising the baseplate heaters and resulting in a longer overall transition.

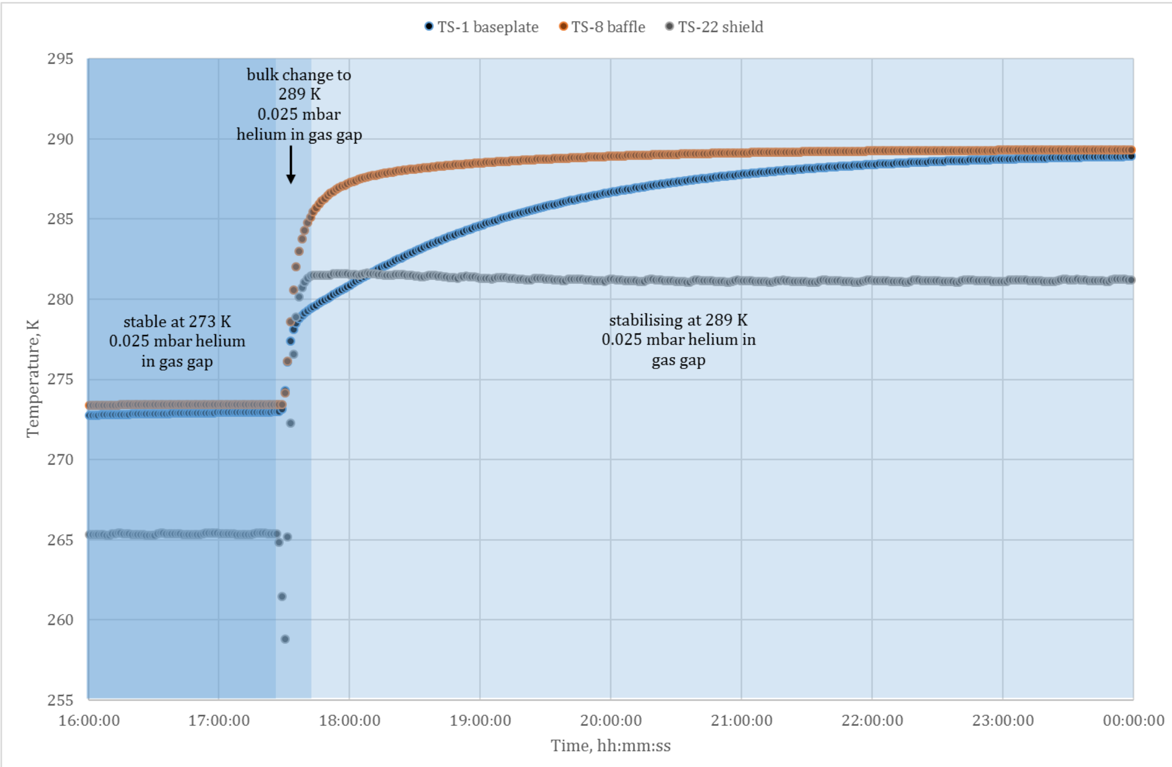

Figure 6 Original heating transition from BBM testing. *It is clear that although the shield and the cavity baffle complete their bulk-change quickly, the baseplate takes much longer to catch up and continues its bulk change during the steady state mode*

When cooling, the helium pressure was altered to match that of the requested temperature set-point, and all heaters were turned off. The system would then cool naturally to the set point when steady state heaters would switch on and maintain the temperature. This process is not optimized due to the manual nature of the testing, this was performed as a proof of concept for the cooling strategy.

C. Phase 2 Testing

The second phase of testing allowed for the preliminary investigation of a revised control method. The main aims were to directly control the baseplate through the radiation and utilise the helium pressure and boost heaters to decrease transition times. A representative investigation was conducted during phase 2 testing that gave confidence in this approach. However, since the hardware was not capable of controlling the shield from a baseplate sensor due to configuration issues with the Eurotherm, the test was conducted manually. Furthermore, the helium pressure was lowered to the intermediate value when the heating occurred in order to limit the influence of the LN_2.

The test involved forcing the shield to a high temperature to increase the driving force heating the cavity base. The aim was to increase the temperature of the baseplate by 16 K. The cavity base has a time constant of about 20 minutes. The radiation shield heaters were thus powered at their maximum output until the baseplate was 8 K below the desired set point. Steady state control was then implemented to stabilize the blackbody at the required temperature. The response of the system is seen in Figure 7. Since the test was conducted manually, the response is not ideal but it proves the aim that the shield can be used to heat the baseplate in a faster and more controlled way.

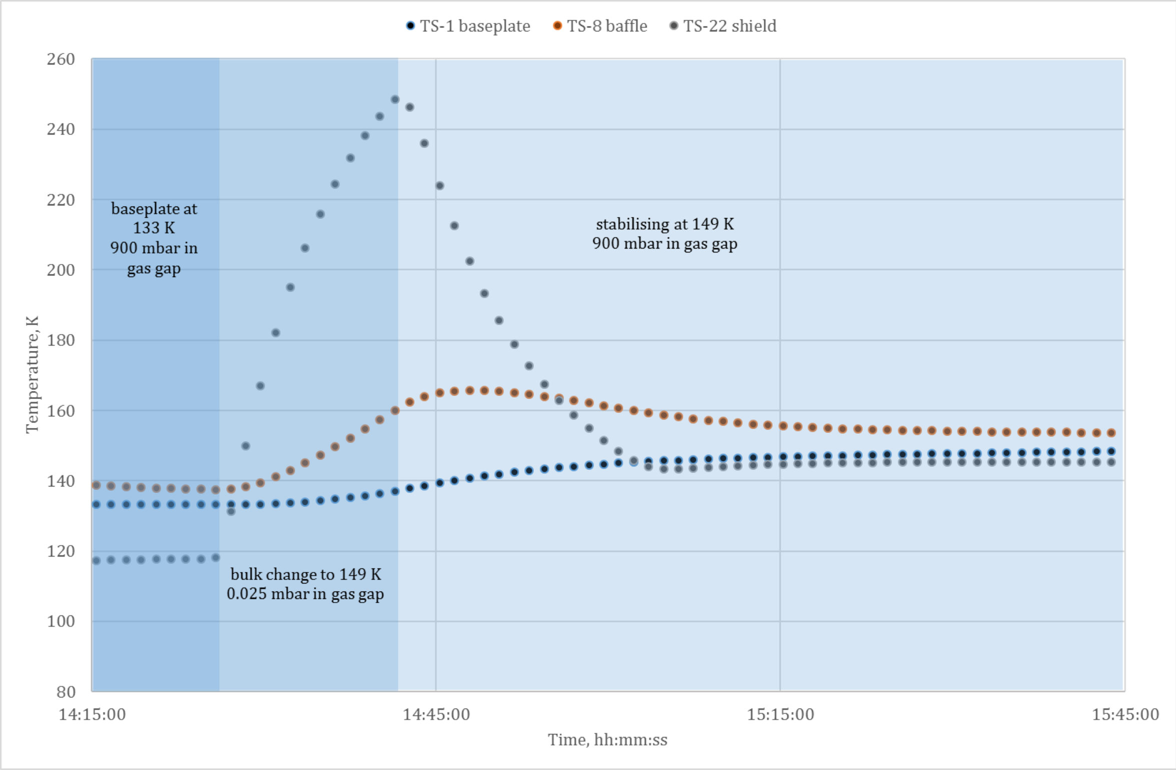

Figure 7 Revised heating transition from BBM testing..

Improving the time of cooling transitions utilised the helium conduction. Increasing the helium pressure in the gap during transition increases the conductive link to the cold LN_2 and thus speeds up the bulk temperature change. Again, due to the slow time constant of the system, the helium pressure would then be changed to that of the requested temperature set-point and steady state control heaters would stabilize the blackbody at the required temperature.

During the phase 2 BBM tests, a pressure of 0.7 mbar was used during the bulk transition. This pressure was chosen as a helium pressure that would not cause helium breakdown, and would not lead to liquid nitrogen being exhausted from the LN_2 jacket. The switch from this 'helium assisted' cooldown to steady state mode was made by monitoring the baseplate temperature and not the temperature of the cavity baffle. Similarly to the heating transition tests, the cooling transition was also controlled manually, and thus although not optimized, provided confidence in the approach for improving cooling transition times.

D. Deliverable Control Strategy

The deliverable strategy will rely heavily on the results of the phase 2 testing. The use of the helium assist and the shield to maintain the baseplate temperature will be utilized.

To combat the naturally slow response of the baseplate, the radiation shield will be used to control the cavity baseplate. This will be achieved by placing the radiation shield control temperature sensor on the baseplate, removing the natural drift of the system and the need to know the temperature offset between the radiation shield and baseplate (shown schematically in Figure 8). The temperature of the radiation shield will be monitored to ensure safe operation, and safeguards will be written into the system to prevent over temperature and damage.

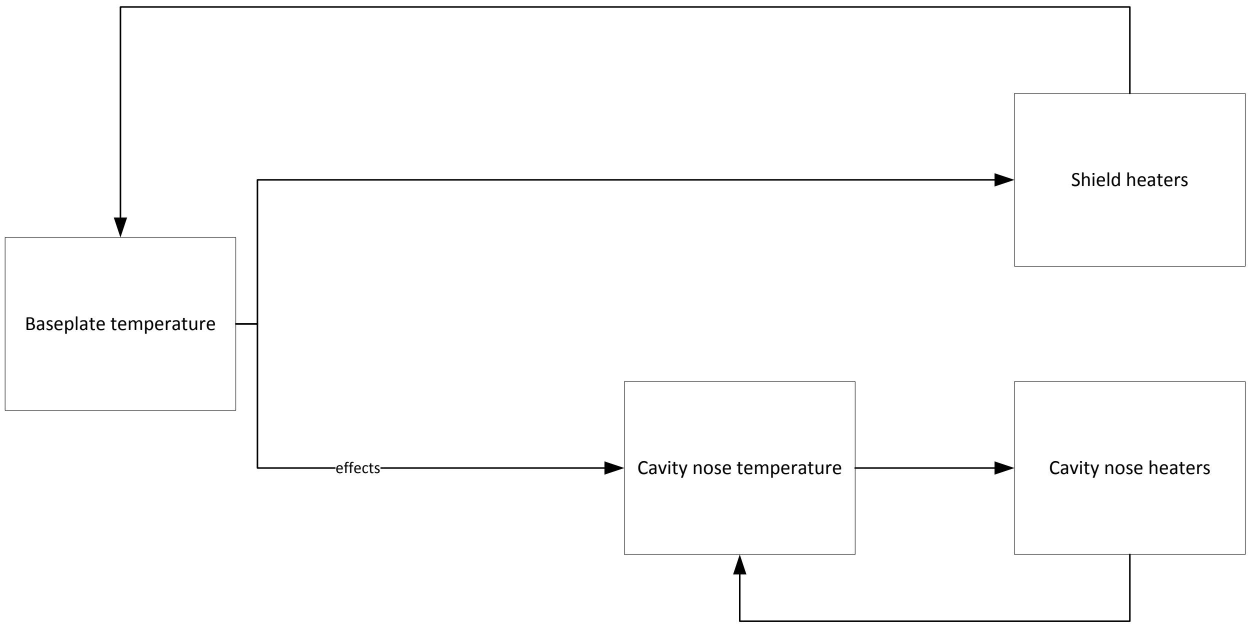

Figure 8 Deliverable control strategy.

The boost mode of the system will be based off of the cavity baseplate rather than the baffle aperture temperature, allowing the system to utilize the extra power in the base heaters for longer.

Helium assist will either accentuate or diminish the effect of the LN_2 when cooling and heating respectively. A vacuum will be introduced for heating transitions, and a higher helium pressure (0.7 mbar, or 900 mbar if already in that range) in the gas gap will improve the cooling transition times.

The software will work automatically to manage all the parameters and will be optimized during the deliverable hardware testing for each blackbody system.

VIII. Conclusion

The use of a helium gas-gap heat switch has proven successful in allowing a broad range of temperatures to be achieved on a large diameter calibration target to a high uniformity and stability. The helium as a solution to the scientific requirements, also became a solution in optimising the practical (time-saving) requirements. The realization of the design has proven challenging; however all but one of the challenges discovered throughout the prototype testing have solutions that are in place and should not affect the operation of the final targets. Investigations into the helium seal are ongoing. The particular focus of optimizing the time taken to transition between two temperatures is driven heavily by customer requirements. The next stage of development is to further optimize the control strategy and to begin the manufacture of the four full-sized (and one smaller) calibration targets for the calibration of the FCI and IRS. Much of the final control strategy system will be defined during commissioning the blackbodies.

Acknowledgments

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