Characterisation of the insulation provided by a carbon dioxide gap for the ExoMars 2018

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The European Space Agency is sending its first rover to Mars as part of the ExoMars 2018 programme. The driving requirements for the Thermal Control Subsystem (TCS) of the Rover Vehicle (RV) are to protect the systems from the large diurnal temperature range on the surface of Mars, while minimising the use of electrical power for heating during the cold nights. The sensitive rover systems are isolated from the external environment and structure with low conductance supports, low thermal conductance harness connectors and by a carbon dioxide 'gas-gap' cavity. A test has been carried out to characterise carbon dioxide gas-gaps for the ExoMars 2018 rover. Three configurations were tested; a configuration with a 30mm sized gap, a configuration with gaps representative of the rover (specifically those greater than 30mm) and a configuration with gaps representative of the rover with convection supressing baffles. The test was designed to simulate the conditions of the Martian atmosphere, with the pressure and temperature adjusted to simulate a similar Rayleigh Number to that on Mars. Testing was carried out in vacuum, carbon dioxide, nitrogen and in air. The performances of the configurations were compared and evaluated.

Nomenclature

ALD = Analytical Laboratory Drawer
CO_2 = Carbon Dioxide
EDL = Entry, Descent and Landing
ENS = Earth Navigation and Science
ESA = European Space Agency
Ls = Solar Longitude
LHP = Loop Heat Pipe
MSL = Mars Science Laboratory
N_2 = Molecular Nitrogen
PEEK = Polyether ether ketone plastic
RHU = Radioisotope Heater Unit
STM = Structure and Thermal Model
SVM = Service Module
TGO = Trace Gas Orbiter
VDA = Vacuum Deposited Aluminium

I. Introduction

ESTABLISHING whether life ever existed or is still active on Mars is one of the principal outstanding scientific questions of our time. To achieve this important objective, ESA intends to launch the ExoMars rover mission in 2018. The ExoMars mission will search for traces of past and present life, characterise the Mars geochemistry and water distribution as a function of subsurface depth, improve the knowledge of the Martian atmospheric environment and geophysics, and identify possible surface hazards to future human exploration missions ExoMars programme.

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The ExoMars programme will be pursued as part of a broad cooperation with Roscosmos. It includes two missions utilising the 2016 and 2018 launch opportunities to Mars, both under ESA leadership. The 2016 mission consists of a Mars Trace Gas Orbiter (TGO) and Entry, Descent and Landing (EDL) demonstrator.

The 2018 mission baseline foresees a Proton launch of a Carrier/cruise module, a 300kg class rover and an EDL module. ESA is primarily responsible for the Carrier and the rover with some technological contribution to the EDL module using heritage from the 2016 mission's EDL system. Roscosmos will be responsible for the overall EDL module including the instrumented platform and will contribute to payloads on-board the rover Vehicle. The rover will carry a comprehensive suite of analytical instruments dedicated to exobiology and geological research: the Pasteur Payload. Over its planned 6 month life, the rover will ensure a regional mobility (several kilometres) searching for traces of past and present life. The rover will be designed and verified for the surface lifetime of 218 sols with a landing at Ls324 within the relatively warm climate between a latitude range of 25ºN to 5ºS.

This paper deals with the thermal control of the ExoMars 2018 mission rover. To protect the internal equipment of the rover from the low temperatures of the Martian environment some form of insulation must be used. The insulation concept used on the rover is to create cavities with a minimum gap between the internal equipment and the rover outer structure. On Mars these cavities will become filled with the Martian atmosphere, low pressure carbon dioxide. A concern is that if convection occurs in these gaps then the insulation performance will be compromised. In a previous paper[1], the concept of using baffles to supress convection in these cavities was examined. This paper furthers that work and investigates the benefits of baffles and the behaviour of gas in larger cavities.

II. ExoMars Rover Configuration Thermal Architecture

The ExoMars rover structure consists of a single-piece moulded sandwich 'bathtub' main body and a solar array panel forming a 'lid'. Inside this structure are two independently thermally controlled modular subassemblies. The Analytical Laboratory Drawer (ALD) comprising of the rover scientific payloads is mounted in the front half of the structure and the service module (SVM) where the warm electronics are located in the rear half of the structure, see Figure II-1.

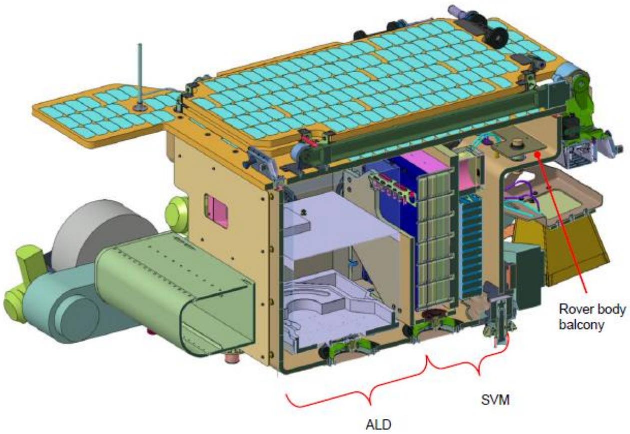


Figure II-1 Rover Body Internal Configuration

The volume inside the rover body is thermally insulated from the external volume and then this internal volume is split in two by an insulating space which separates the modules described above. The temperature of each module is managed using radioisotope heater units (RHU) and loop heat pipes with thermostatic valves (LHP). The RHUs are used to keep the rover warm during the night and the LHPs are used to reject excess heat during the day. The effectiveness of this architecture is based on minimising heat lost by each of the modules. The radiative coupling is managed by the use of low emissivity coatings on the bathtub and rover internals. The conductive couplings through the mechanical interfaces between the bathtub and the rover internals are managed by use of insulating stand-offs. The conductive couplings through the harness between the bathtub and the rover internals are managed by use of low thermal conductance bulkhead connectors and use of cable trays. This leaves one remaining coupling which needs to be assessed and managed, the one through the gas within the bathtub. Figure II-2 below is a cross section of the rover SVM illustrating the rover thermal architecture.

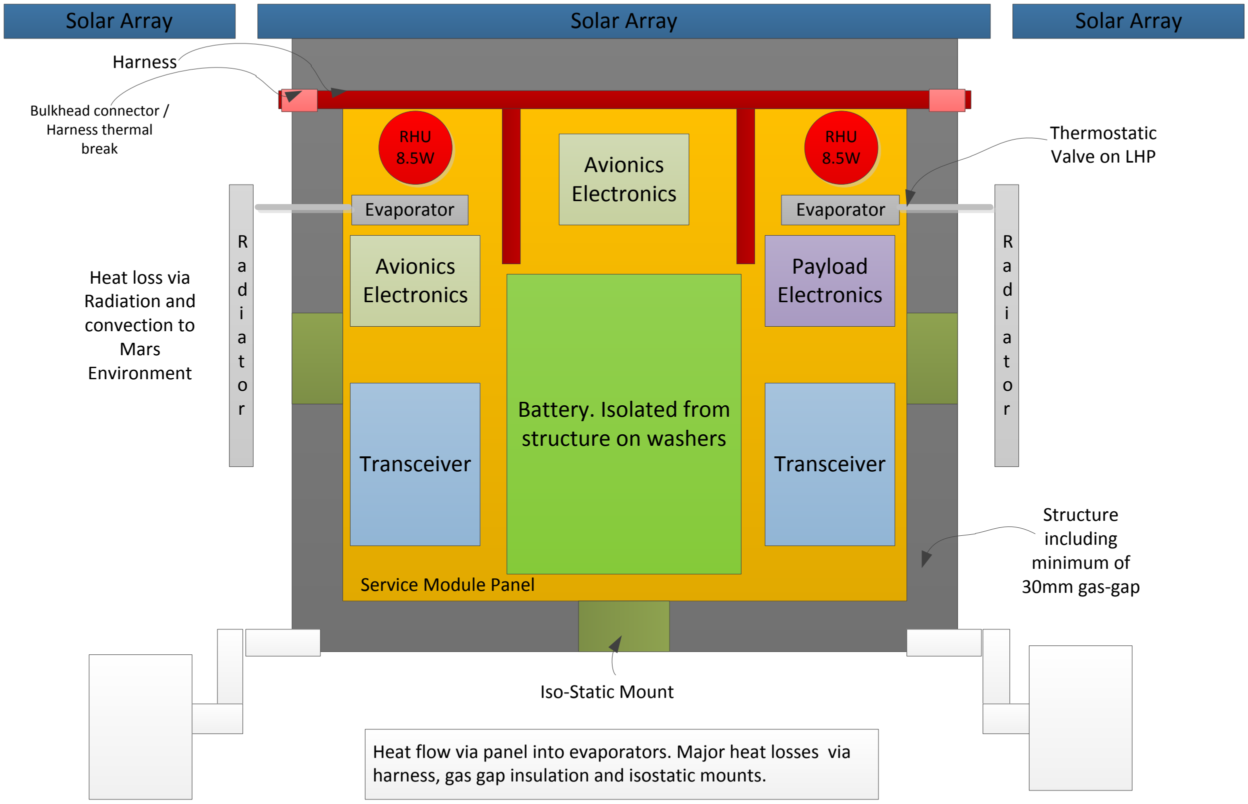


Figure II-2 Schematic of the rover SVM thermal architecture

III. Carbon Dioxide 'Gas-Gap' insulation design

The coupling through the gas introduces an unusual thermal design challenge due to the fact that convection may occur in the cavity between the rover bathtub and internals. If convection occurs the concern is that this may produce an unacceptably large coupling between the bathtub and rover internals. Furthermore convection is a complex phenomenon to model. Two potential approaches exist to assess and manage the coupling through the gas: suppress convection in the cavity, which also simplifies the coupling; or demonstrate that convection effects are acceptable. There are several potential ways in which convection could be suppressed: by displacing the gas (for example by placing aerogel in the cavity); by entraining the gas (for example by placing an open cell foam in the cavity); or by pocketing and baffling the gap with small cavities which are too small for convection to start.

The solution adopted on the ExoMars rover was to use baffles to create cavities which are too small for convection to start. A baffle structure was designed that supported a film a fixed distance from the structure of the rover and this cavity was then broken down further into smaller pocketed areas. Baffles were selected due to contamination and procurement issues associated with foam and aerogel[1]. The concept of the baffled design was demonstrated in two tests[1, 2]. These tests showed that for a temperature difference of 50°C and a pressure of 7 mBar, a gap of 30 mm or less will always suppress convection. This design resulted in a complex network of baffles consisting of films mounted to a support structure attached to the bathtub structure as can be seen in Figure III-1.

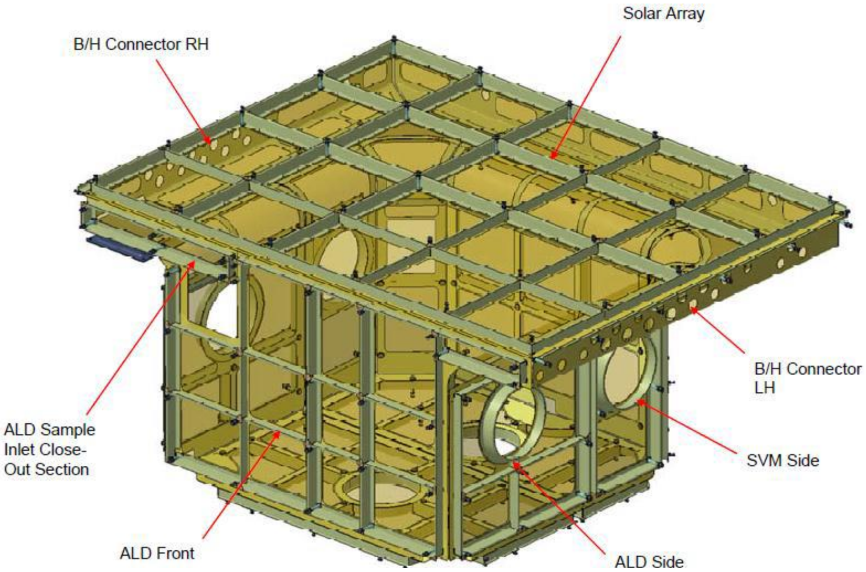


Figure III-1 30mm baffle network

It became apparent, based on work carried out at JPL for their MSL Mars rover, that with care, it may be possible to design the gaps[3] between the components and the structure walls such that the baffles could be removed from some areas. Limitations were also noted with the testing already carried out; despite the design supressing convection in the area adjacent to the structure the behaviour of the gas in the cavities and gaps around the modules were not well understood, the temperature and pressure ranges tested did not represent the extremes predicted for the rover.

With this in mind a test was defined with the following objectives:

- Determine whether convection occurs for the gap sizes and temperature differences expected inside the rover
- Provide sufficient data to correlate thermal models predicting the insulation performance of the gas gap
- Validate whether using N_2 gives the same thermal performance as CO_2 (N_2 can be used instead of CO_2 to simplify the STM test)
- Compare insulation performance with and without baffles

IV. Test Definition

The test article and parameters were selected to be representative of the rover. The target temperatures were defined using the outputs of the rover thermal analysis. This analysis indicated that the largest gradient expected was just before dawn in one of the cold cases when a gradient of 130°C was predicted between an RHU (+20°C) and part of the structure (-110°C). An area of concern was that a hot unit on a cool panel may initiate convection. In the rover the largest gradient was 25°C between the RHU and the panel on which is it mounted. To simulate this a hotplate was mounted in the centre of one face of the test article.

A target representative Mars surface pressure of 10 mBar was selected for the test. Tests with CO_2 and N_2 were planned with N_2 being used to enable testing at temperatures below which CO_2 deposits. Testing at the representative Martian pressures and temperatures replicates both the Rayleigh number (which governs the onset of convection[4]) and the coupling due to convection.

The geometry and configuration of the rover modules are complex. To simplify the test article and ease the interpretation of the results the dimensions of the test article were sized according to the largest cavities and gaps present inside the rover (see Table IV-1). The test articles took the form of a box within another box which was reconfigurable into three configurations;

- Configuration 1 – representing a baseline set-up with a uniform 30 mm gas gap around all faces of the box, similar to the previous testing reported[1].
- Configuration 2 – with a smaller box positioned asymmetrically inside the external box to give the gaps listed in Table IV-1 which are representative of the gaps in the rover and cover the range at which convection is expected to be induced.

- Configuration 3 – which uses the same arrangement of gaps as Configuration 2, but with baffles fitted to all internal faces of the external box such that there is a 27mm gap between the External Box and the baffles.

In Configurations 2 and 3 a hotplate it is attached to the centre of the left +Y vertical face. These test article configurations are shown in Figure IV-1.

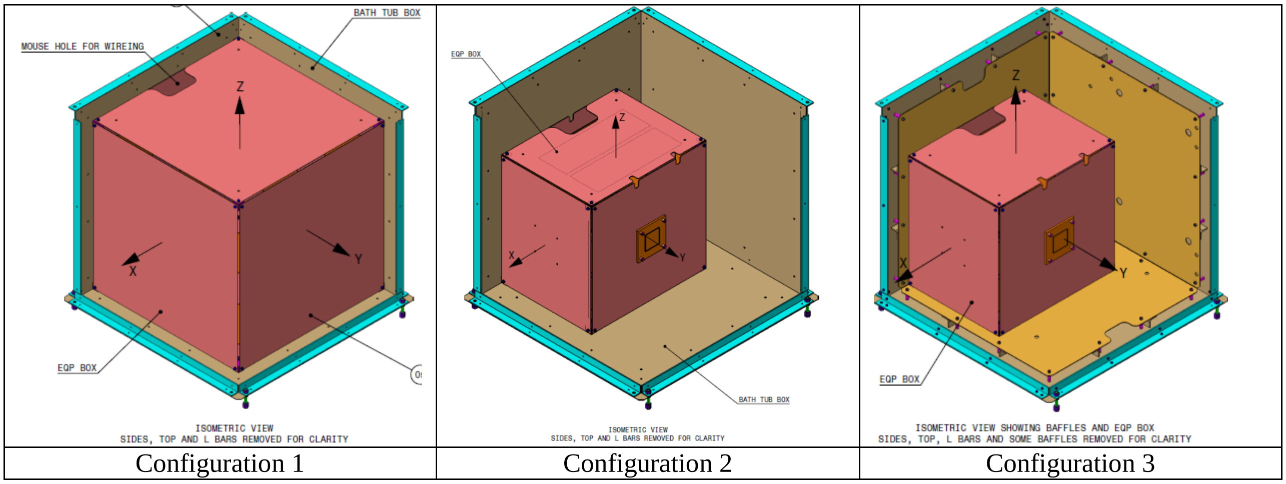
For each configuration the following balances were planned:

- Balance in Ambient – To provide an indication of what will happen on earth prior to launch
- Balance in Vacuum – To quantify the radiative heat transfer
- Balance in CO_2, 60°C gradient between boxes – A typical gradient between a warm unit and the cold structure
- Balance in N_2, using CO_2 heater powers – To enable a direct comparison between N_2 and CO_2
- Balance in N_2, 60°C gradient between boxes – A typical gradient between a warm unit and the cold structure
- Balance in N_2, 130°C gradient between boxes – The maximum gradient between a warm unit and the cold structure

Additionally, for Configurations 2 and 3 balances with the hotplate set to create a 25°C gradient between it and the face on which it was mounted were planned.

Gas Gap	Configuration 1	Configuration 2	Configuration 3
Top +Z	30 mm	165 mm	165 mm
Bottom -Z	30 mm	30 mm	30 mm
Front +X	30 mm	60 mm	60 mm
Rear -X	30 mm	120 mm	120 mm
Left +Y	30 mm	240 mm	240 mm
Right -Y	30 mm	30 mm	30 mm
Baffles?	NO	NO	YES, all faces

Table IV-1 Test Gap Configurations



Configuration 1 Configuration 2 Configuration 3

Figure IV-1 Test article configurations

V. Test Setup

The test was performed in the high power test thermal chamber, Figure V-1, at the in-house environmental test facilities at Airbus Defence and Space Ltd in Stevenage. The chamber contains a box shroud with six independently controllable shrouds. Each shroud operated using a gaseous and liquid nitrogen mix which was computer controlled by a feedback loop to the requested shroud temperature.

To control the atmosphere for the test the chamber was first pumped to a hard vacuum. A roughing pump was then used and the desired gas was bled into the chamber. A computer controlled valve was used in conjunction with a pressure sensor to maintain the gas at the required pressure.

The test articles, Figure V-2, consisted of a common external aluminium box, two internal boxes and a set of baffles. The internal cavity was coated with vapour deposited aluminium (VDA) Kapton to minimise the radiative transfer between the boxes. The baffles and boxes were held in place and thermally isolated from each other using polyether ether ketone (PEEK) plastic standoffs and brackets. The baffles were constructed of thin sheets of fibre-glass coated with low emissivity VDA Kapton.

To control the temperature of the boxes large flat foil heaters were bonded to each face. Each heater was connected to a manually controlled power supply unit. Guard heaters were used to prevent any heat loss down the harness bundles.

It was intended to monitor the gradients across each face of the box using nine thermocouples. However several faces had to be instrumented with fewer thermocouples as the chamber was limited to 101 thermocouples. Type T thermocouples with a measurement tolerance of ±1°C were used.

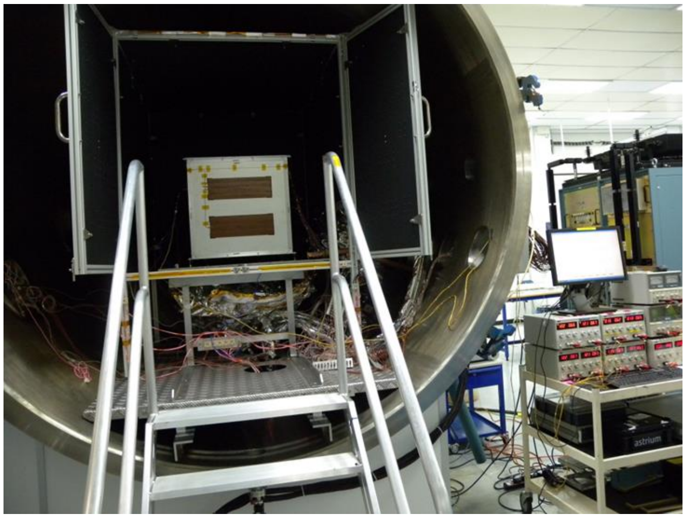
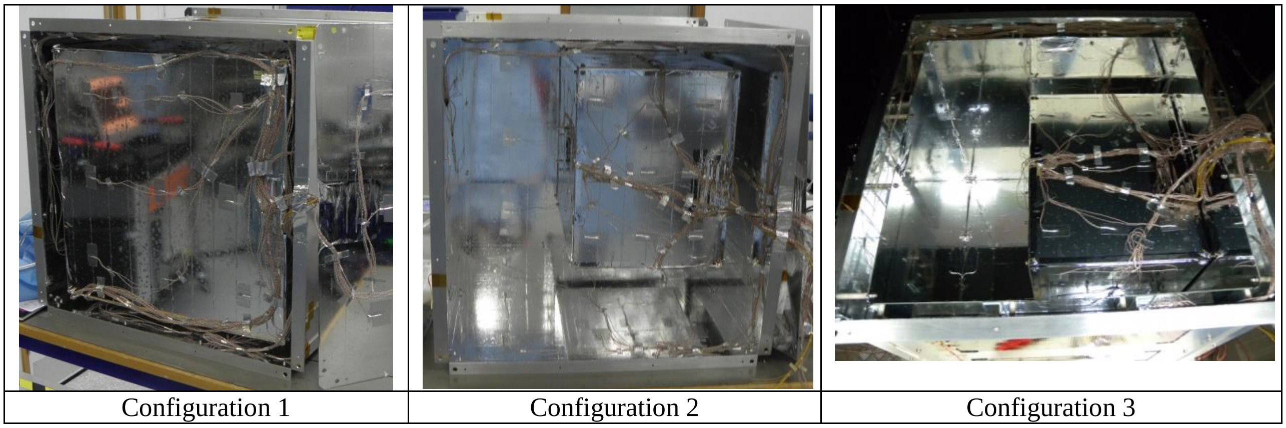


Figure V-1 Test article in the High Power Test thermal chamber



Configuration 1	Configuration 2	Configuration 3

Figure V-2 Test articles

VI. Test Summary

During Phase 1 of testing it became apparent that the test chamber was unable to go cold enough to achieve the box target temperatures with gas present inside the chamber. With CO_2 in the chamber the shrouds could not be cooled further due to the shroud inlet temperature approaching the deposition temperature of CO_2. With N2 in the chamber the cooling limit of the shrouds was reached, the shroud temperature could not be lowered whilst maintaining a stable temperature. The presence of gas inside the chamber places a greater load than normal on the shrouds since the gas couples the shrouds to the outer wall of the chamber. To resolve these problems a custom shroud would be needed which was insulated the shrouds from the chamber walls and was closer to (and consequently better coupled to) the test article.

Consequently this meant that although the desired gradients were achieved the average temperature was higher than desired. This effectively lowered the Rayleigh number reducing the likelihood of the onset of convection. To compensate for this and raise the Rayleigh number the pressure in the CO_2 cases was increased to 15.5 mBar and in the N_2 cases to 19.0 mBar. This ensured that the amount of convection observed in the test is at least as much as the worst expected case on Mars.

The drawback with this approach is that the coupling due to convection varies with pressure differently to the way the Rayleigh Number varies with pressure. This means that the Gas Gap Test cannot simultaneously reproduce the Rayleigh Number and the coupling due to convection expected in the worst case on Mars. The Gas Gap Test was designed to investigate the magnitude of convection experienced in the Gas Gap of the rover and so the pressures for Gas Gap Test were selected such that the Rayleigh Numbers would match those in the worst case on Mars. Thus the Rayleigh numbers and the potential for convection were replicated but the coupling due to convection in the Gas Gap Test will be larger than that expected for the rover on Mars.

VII. Test Results

Several conclusions can be drawn from the test results, these are reported hereafter.

A. Effect of Size of Gap

The relationship between the heater power per unit area required to maintain a temperature gradient over a given gap size is reported in Figure VII-1. For gaps less than 60 mm the heater power decreases with gap size indicating conduction is occurring. For gaps greater than 60 mm the heat loss through the gas then increases with gap size (with a slight anomaly on the 165 mm gap which is explained by the fact that this is a horizontal rather than a vertical gap), suggesting that convection is occurring in the 120 mm and 165 mm gaps. The trend observed agrees with textbook equations[4] and previous tests[3]. These textbook equations and previous tests do not account for the 3D nature of the test article. The differing results observed for the 30mm gaps are attributed the edge effects caused by the geometry of the test article.

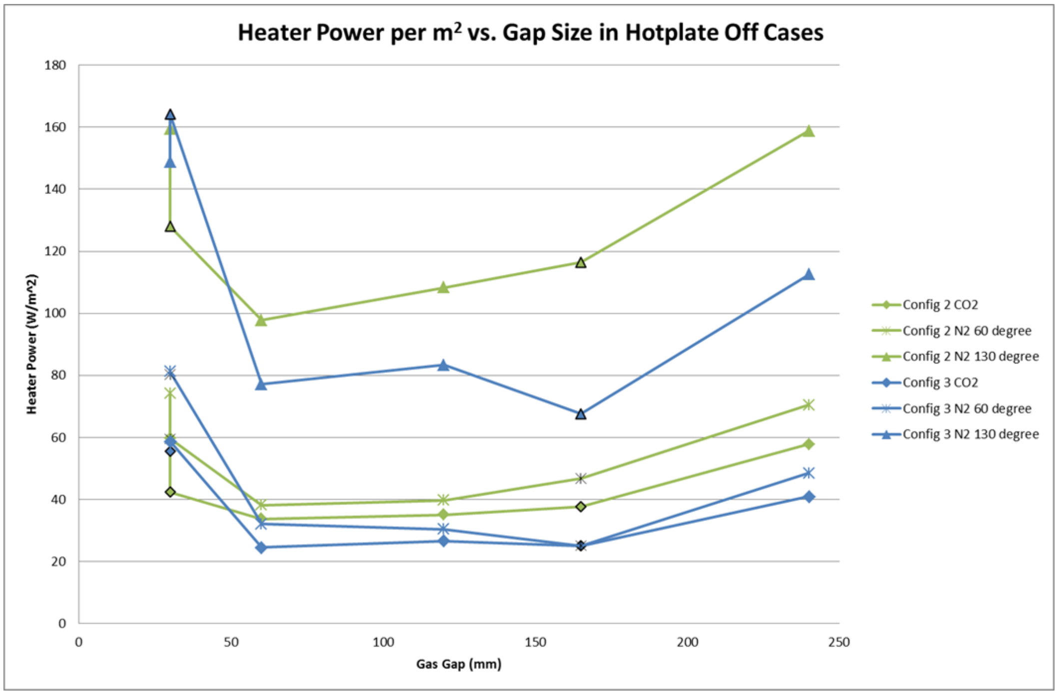


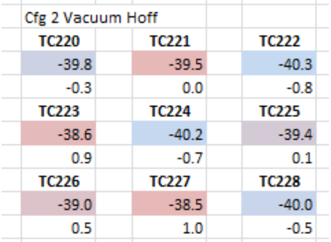
Figure VII-1 Heater Power per m^2 applied to Face versus Gap Size (the horizontal gaps have been outlined in black and the radiative heat flow contribution removed)

B. Presence of Convection

The presence of convection is indicated in Figure VII-1 and is physically demonstrated in Table VII-1. The +Y face is adjacent to the largest cavity in Configuration 2 and a clear gradient can be seen up the face of the external box. This gradient, which is not present in the vacuum case, is attributable to convection occurring inside the cavity.

In the course of setting the heater powers during the Configuration 2 tests it was noticed that a heater change on one face of the box would cause an immediate response on another face during the gas phases but not during the vacuum phases or during the Configuration 1 tests. The rapid nature of the response indicates that the heat is being convectively transported through the cavity between the boxes.

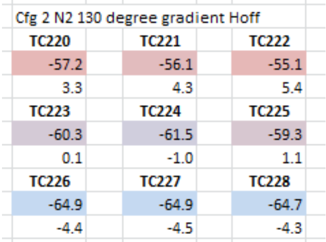
No convection was observed during the testing of Configuration 1 which has 30 mm gaps. This indicates that convection does not occur within a large cavity with a gap spacing of 30 mm and that it is not necessary to pocket these gaps.



Cfg 2 Vacuum Hoff

TC220	TC221	TC222
-39.8	-39.5	-40.3
-0.3	0.0	-0.8
TC223	TC224	TC225
-38.6	-40.2	-39.4
0.9	-0.7	0.1
TC226	TC227	TC228
-39.0	-38.5	-40.0
0.5	1.0	-0.5

Configuration 2, Vacuum



Cfg 2 N2 130 degree gradient Hoff

TC220	TC221	TC222
-57.2	-56.1	-55.1
3.3	4.3	5.4
TC223	TC224	TC225
-60.3	-61.5	-59.3
0.1	-1.0	1.1
TC226	TC227	TC228
-64.9	-64.9	-64.7
-4.4	-4.5	-4.3

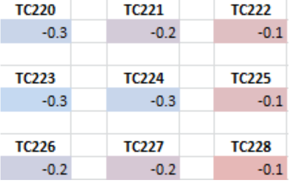
Configuration 2, N_2, 130°C gradient between boxes

Table VII-1 Temperature Gradients on +Y Face of the External Box for Configuration 2 in vacuum and N_2 with a 130°C gradient (Note: Numbers in the coloured boxes are the temperatures of the thermocouples, the numbers immediately below the thermocouple temperatures are the difference between the thermocouple temperature and the average temperature of the +Y face in that balance).

C. Hotplate On/Off

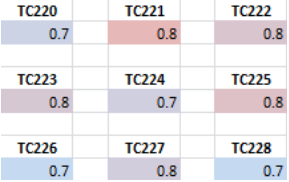
Balances with the hotplate located on the +Y face of the internal box were performed during the testing of Configurations 2 and 3. In these phases the hotplate was heated such that it was 25°C hotter than the average temperature of the plate on which it was mounted. The aims of these tests were to investigate whether a hot unit on a cooler panel would drive convection across the rest of the panel.

In all cases it was found that turning the hot plate on increased the total heater power by less than 3.2% with respect to having the hot plate off. Given that the total heater power applied to the +Y face of the internal box remained similar in the hotplate on and off cases it would be expected that the external box +Y face would be warmer if the hotplate boosted convection. In Table VII-2 it can be seen that this is not the case. Consequently it appears that it is the total energy into the gap which drives the amount of convection.



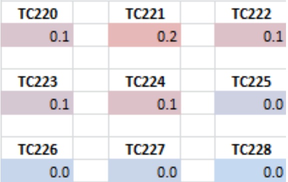
TC220	TC221	TC222
-0.3	-0.2	-0.1
TC223	TC224	TC225
-0.3	-0.3	-0.1
TC226	TC227	TC228
-0.2	-0.2	-0.1

Configuration 2, Vacuum



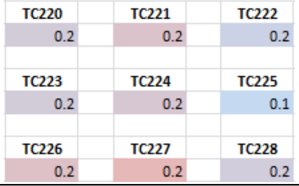
TC220	TC221	TC222
0.7	0.8	0.8
TC223	TC224	TC225
0.8	0.7	0.8
TC226	TC227	TC228
0.7	0.8	0.7

Configuration 2, CO_2, 60°C gradient between boxes



TC220	TC221	TC222
0.1	0.2	0.1
TC223	TC224	TC225
0.1	0.1	0.0
TC226	TC227	TC228
0.0	0.0	0.0

Configuration 2, N_2, 60°C gradient between boxes



TC220	TC221	TC222
0.2	0.2	0.2
TC223	TC224	TC225
0.2	0.2	0.1
TC226	TC227	TC228
0.2	0.2	0.2

Configuration 2, N_2, 130°C gradient between boxes

Table VII-2 Temperature differences between the hotplate on and off cases for the +Y face of the external box

D. Comparison of Baffled and Non-Baffled

Configurations 2 and 3 are identical except that Configuration 3 has baffles mounted on the internal face of the external box. This allowed for a direct comparison between the insulation improvements provided by baffles. The baffles reduced both the radiative and convective heat transfer between the internal and external boxes.

Overall introducing the baffles reduced the total heater power needed to achieve the gradients by approximately 20%. The largest reductions were seen on the +Z face with reductions in heater power of approximately 40%. This is expected as hot gas from the sides of the Internal Box as well as the air directly above the Internal Box will convect up towards the +Z face, therefore the baffles on the +Z face are preventing heat loss from the sides and upper face of the internal box. For the faces (–Y and –Z) with 30 mm gaps, where convection is expected to be already suppressed, little improvement was seen (with a decrease of 10% for –Y and an increase of 20% for –Z). The reason for the increase on the –Z face is thought to be caused by heat flowing through the baffle itself which was more conductive than gas where there is no convection occurring. It is thought that this is less noticeable on the –Y face due to convection occurring in the area of the face adjacent to the open cavity. In this area adding the baffle would reduce the heat loss whereas adding the baffle in the area of the 30 mm gap between the internal and external box it would increase it.

E. Comparison of CO_2 and N_2

The textbook equations predict that for the same pressure and temperature gradient the heat loss through N_2 is greater than through CO_2. This was confirmed in the test results. When the same heater powers were applied to the Internal Box in CO_2 at 15.5 mBar and in N_2 at 19.0 mBar the Internal Box temperature was:

- 8.0°C cooler in N_2 in Configuration 2 with the Hotplate Off
- 8.7°C cooler in N_2 in Configuration 2 with the Hotplate On
- 11.4°C cooler in N2 in Configuration 3 with the Hotplate Off
- 11.0°C cooler in N2 in Configuration 3 with the Hotplate On

The differences in Internal Box temperature between N2 at 19.0mbar and at 15.5 mbar when the same heater powers were applied were:

- 1.5°C cooler in at 19.0 mbar in Configuration 2 with the Hotplate On
- 0.8°C cooler in at 19.0 mbar in Configuration 3 with the Hotplate Off

The increase in heat loss through the gas at a higher pressure is attributed to an increase in the convective coupling between the boxes. Gas conduction does not vary significantly between the two pressures tested however the density of the gas does and the convective coupling through a gas is proportional to the square root of the density of said gas[4]. This can be seen in the results as the heat loss is less in Configuration 3 where the baffles limit the amount of gas where convection can occur.

In summary the heat loss through N_2 is greater than through CO_2 and increasing the pressure increases the heat loss through the gas when convection is present.

VIII. Conclusions

The following conclusions can be drawn from the analysis of the Gas Gap Test results conducted so far. Further conclusions may be possible once the thermal model correlation has been completed:

- Convection occurs within 240 mm, 165 mm and 120 mm Gas Gaps at Martian representative Rayleigh Numbers
- Convection does not occur within 30 mm gaps and significant convection is not observed in 60 mm Gas Gaps at Martian representative Rayleigh Numbers
- Having a hot unit present on a cooler panel, with a 25°C gradient between the two, does not drive the amount of convection occurring within a Gas Gap, compared to the same panel with the hot unit switched off
- Installing baffles increases the insulation performance of Gas Gaps greater than 30 mm
- Installing baffles does not significantly increase the insulation performance of Gas Gaps less than 30 mm, and can actually reduce it in some cases
- Installing baffles appears to improve the insulation performance the most on the +Z face of the test article
- Installing baffles appears to reduce the insulation performance the on the –Z face of the test article
- With shrouds set to the same temperature and the same heater powers applied, a larger heat loss was experienced by the test article in N2 compared with CO2, as was expected

Based on these conclusions the rover thermal baffling concept was updated to remove the pocketing from the baffles and eliminate the baffles on the bottom (–Z) of the rover and in the areas where the structure already creates a 30 mm gap.

A correlation and evaluation of modelling techniques is currently being performed. The correlation will provide more information on the differences between: horizontal and vertical gaps, CO_2 and N_2, and the radiative and convective performance of the baffles. It is planned to report these findings in a future paper.

Acknowledgments

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