Thermal Storage Unit Using the Triple Point of Hydrogen

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ABSTRACT

The French space agency (CNES) has co-funded a Research and Technology program and CEA/SBT has developed a 14 K thermal storage unit using the triple point of hydrogen. The development unit is able to store 10 J at 14 K. The unit has been tested at various peak loads in order to validate the energy stored and to measure the temperature stability. This thermal buffer could be used in a cryogenic space mission subject to variable heat loads. The design of the unit will be described and the thermal results will be presented.

INTRODUCTION

The use of mechanical cryocoolers to achieved low temperature has seen widespread use in the last decade. Contrary to a standard helium bath, the instantaneous cooling power delivered by these coolers is limited. For some applications, the cryogenic load is time-variant and a Thermal Storage Unit (TSU) is being proposed to deal with the peak power. By using a TSU, the cryocooler can be sized to the average cooling power need rather than the maximum need. For space applications, Planck opened the way of the low temperature cryogen free satellite and some other missions under study like SPICA and IXO will use the cryogenic chain to achieve sub-Kelvin temperatures. For IXO, one potential solution for the last stage of the cryogenic chain is the sorption cooler coupled with an ADR developed in our laboratory[1]. This system requires rejecting heat during the recycling phase to the upper temperature stage. In the IXO design, some heat will be rejected at the 15 K and the 2.5 K locations where limited cooling power is available. To limit the temperature drift, the heat rejected by the sorption cooler has to be limited and controlled. The aim of the TSU presented in this paper is to demonstrate the capability of using the latent heat of the triple point of hydrogen to adsorb a peak heat load around 14 K. This could simplify the control of the heat rejected by the sub-Kelvin cooler and hasten its recycle time.

OBJECTIVES OF THE WORK

Under a CNES Research & Technology contract, we studied the feasibility of using the latent heat of the triple point of hydrogen at 13.8 K in a thermal storage unit. The goal was to design, build and test a unit able to adsorb 10 Joules. The temperature drift at the peak load is to be minimized and the unit should be designed to work in microgravity.

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DESCRIPTION OF THE PROTOTYPE

The prototype is made of copper, “the thermal bus”, in which thin slots (0.2 mm) have been manufactured by electro-discharge machining (see Figure 1). These slots are used to collect the hydrogen liquid during condensation prior to freezing. The volume of the slot has been designed to collect the amount of liquid corresponding to 10 joules. The latent heat of fusion of hydrogen at 13.8 K is 58.5 J/g and the liquid density is 0.077 g/cm^3 which leads to a volume of 2.22 cm^3.

The design was made to be compatible with a single volume mode[2], i.e. just one cold volume sealed at room temperature. To deal with the pressure constraint, the diameter of the cell has been limited to 30 mm. For manufacturing reason, it does not seem reasonable to decrease the thickness of the fins between the slots to a value lower than 1 mm. With this fin thickness value, the number of slots that can be machined is 23. The length of the fins (or deepness of the slots) is then imposed by the volume of liquid that needs to be confined. The length is limited to 18.9 mm. Obviously, there is a need to have a closed cell and a cap that cover the thermal bus is made of stainless steel. This cap and the thermal bus are brazed with a silver base braze. A filling port has been installed into this cap. The cell is designed to be sealed at a warm temperature with the required amount of hydrogen inside. The warm pressure has been taken to 80 bars as a sealing technique: this pressure is well known in our laboratory (experience with helium sorption cooler). This implies that a large volume, more than 10 times the volume of the slots has to be managed into the cell. This is shown in the Figure 1 (right). In practice, for the thermal test in lab, the cell was not sealed and has been connected via a small capillary to a warm volume (dual volume configuration)[3]. This allows the adjustment or modification of the amount of hydrogen and relaxes the safety aspects. The warm volume is a 1.9 liters stainless steel volume. The whole unit is filled with 1.2 bars of hydrogen. A valve has been introduced into the connection line between the cold volume and the warm volume in order to be able to simulate the cold behavior of a sealed cell by closing the valve when the system is cold.

The thickness of the slots (0.2 mm) has been taken as low as possible in order to limit the thermal gradient into the hydrogen. With the assumption that the axial thermal gradient in the fins are negligible, a homogeneous liquid film will form at the interface between cooper fins and solid hydrogen trapped into the slots. This film will grow until the solid hydrogen which also has a film shape will disappear at the center of the slots. This phenomenon is notationally represented in Figure 2. It is possible to put a number on the thermal resistance (R_{th}) of the liquid film at the end

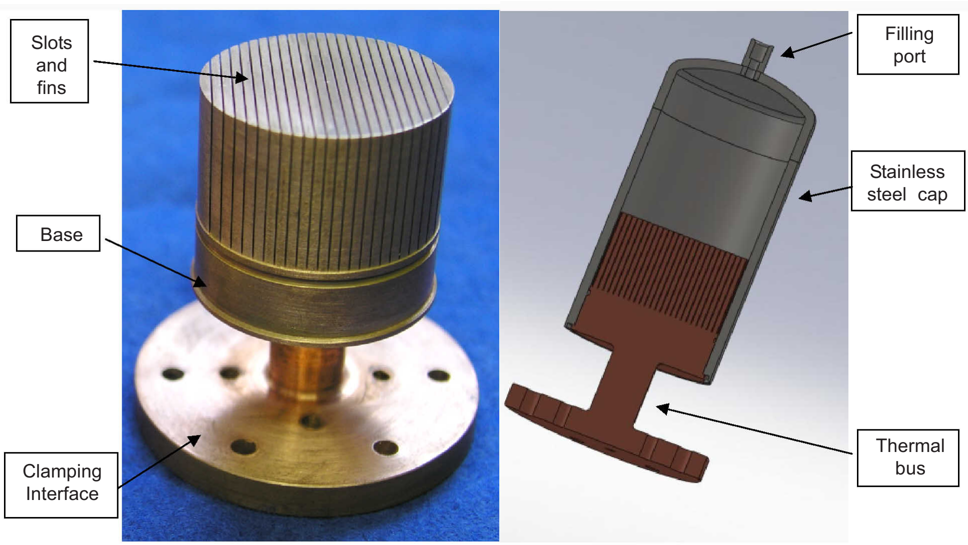

Figure 1. The thermal bus (left) and complete cold unit (right)

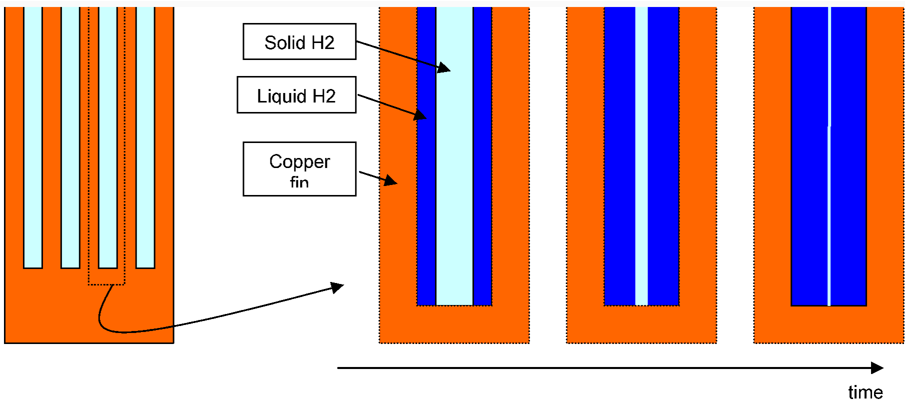

Figure 2. Time evolution in a slot during warm up of hydrogen ice

of the warm up. This thermal resistance depends on the slots gap (gap), the surface of the fins (S_{fins}) in contact with the hydrogen and the conductivity of the liquid hydrogen (k_{liq}).

$$1/R_{th} = \frac{S_{fins}}{\frac{gap}{2}} \cdot k_{liq} \tag{1}$$

Only half of the gap is taken into account as the last piece of solid is assumed to be in the middle of the slot.

As the volume of the liquid (V_{liq}) is fixed, there is a relation between the surface of the fins, the gap, and the volume of liquid.

$$V_{liq} = \frac{S_{fins}}{2} \cdot gap \tag{2}$$

The factor 2 comes from the fact that only one side of the slot volume should be used to calculate the volume. So Eqn. (1) becomes

$$1/R_{th} = 4 \cdot k_{liq} \cdot \frac{V_{liq}}{gap^2} \tag{3}$$

As is seen in the last equation, the slot gap is a strong driver for the thermal gradients in the cell. For a 0.2 mm gap slot, taken at a thermal conductivity of 0.073 W/m/K for the liquid hydrogen, the thermal resistance is 62 mK/W.

The thin slots also allow the trapping of liquid hydrogen by capillarity even when the cell works against gravity.

The clamping interface is equipped with a Cernox thermometer and a resistive heater.

The mass of the cold volume is around 332 g. This mass could be reduced to 282 g by reducing the clamping interface dedicated to this project.

TEST BENCH

A diagram and photograph of the test setup is found in Figure 3. The cell unit is cooled using a two-stage Gifford McMahon (GM) cooler from CTI (M1020 CP). In the temperature range foreseen for operation (around 14 K), GM coolers are known to produce large thermal fluctuations (larger than 1 K) with the same frequency as their operating frequency. To provide a cold interface with stable temperature, a copper plate was mounted to the second stage of the GM cooler via a stainless steel spacer (shunt) which acts as a thermal damper. The TSU was then mounted on this copper plate. In order to limit and to measure the heat flux leaking from the TSU to the copper plate, a thermal shunt (stainless steel spacer) has been inserted between these 2 parts. A thermal shield which is mounted on the copper plate protects the TSU from thermal radiation. A thermal regulation is used to choose the temperature of the copper plate and to compensate for the GM temperate drift.

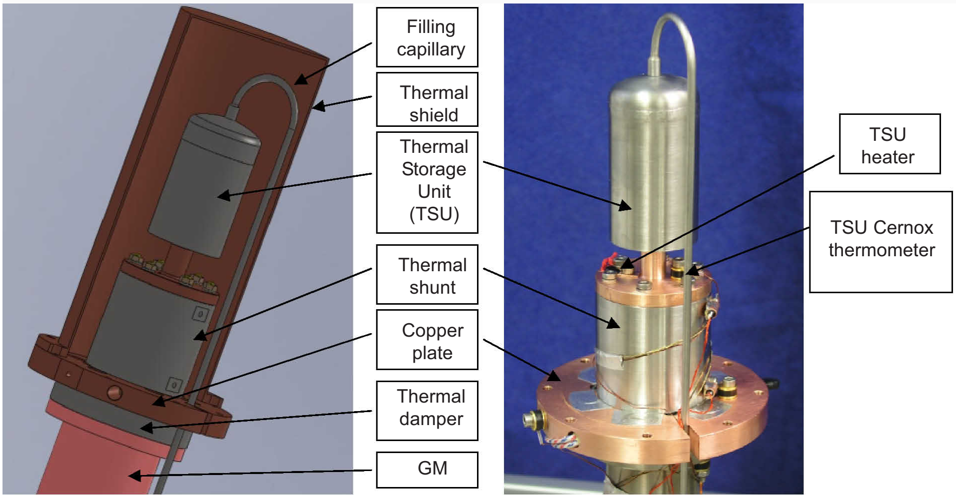

Figure 3. Thermal storage unit mounted on the second stage of the GM: 3D drawing (left), picture of the unit with its instrumentation (right)

THERMAL TEST RESULTS

Measurement Description

For the first test, the cell unit is cooled from room temperature. Due to the large room temperature volume filled at 1.2 bars, the pressure inside the setup did not vary greatly during the cooldown, and the condensation of hydrogen occured near 20 K. The liquid is then cooled until the triple point (around 13.8 K) where solid hydrogen starts to appear. When all the liquid is transformed into solid, the temperature of the cell restarts to decrease. The temperature of the copper plate is regulated around 13.5 K, to force the cell unit to be at a temperature just below 13.8 K. The temperature of the cell unit is slightly above the copper plate due to the small thermal gradient into the shunt induced by the TSU parasitic losses. The experiment is maintained in this state for a period of time to achieve a good thermal stability, then the heater located at the base of the thermal storage unit is switched to a constant value. Power values from 10 mW to 1000 mW have been experienced. When the heating power is applied, the temperature of the cell unit increases very quickly up to a temperature just above 13.8 K and then stabilizes as a plateau (see Figure 4). At the end of the plateau the increase of temperature resumes and the applied load is switched off. The temperature then decreases due to cooling by the GM cryocooler and a new cycle can be performed with a different load.

Data Treatment

From the TSU temperature measurement, we want to extract the amount of energy stored to define the thermal stability that can be achieved with this apparatus as a function of the load applied.

The energy stored is equal to the load applied to the TSU multiplied by the time duration. The load applied to the TSU corresponds to the load applied by the heater minus the heat flow through the shunt towards the copper plate regulated at 13.5 K. This thermal leak has been calibrated and the heat flow is known. The duration of the plateau is somewhat difficult to determine as already mentioned by other authors[3]. In general, the beginning of the plateau is well defined but this is not the case for the end of the plateau. To apply the same criteria to estimate the duration of the plateau for each measurement, we decided to plot 3 extra curves on the measurement. The first one is a fit (exponential shape) of the first temperature increase, the second is a linear fit of the plateau and the third one is a fit (exponential shape) of the second temperature increase. It is possible to determine

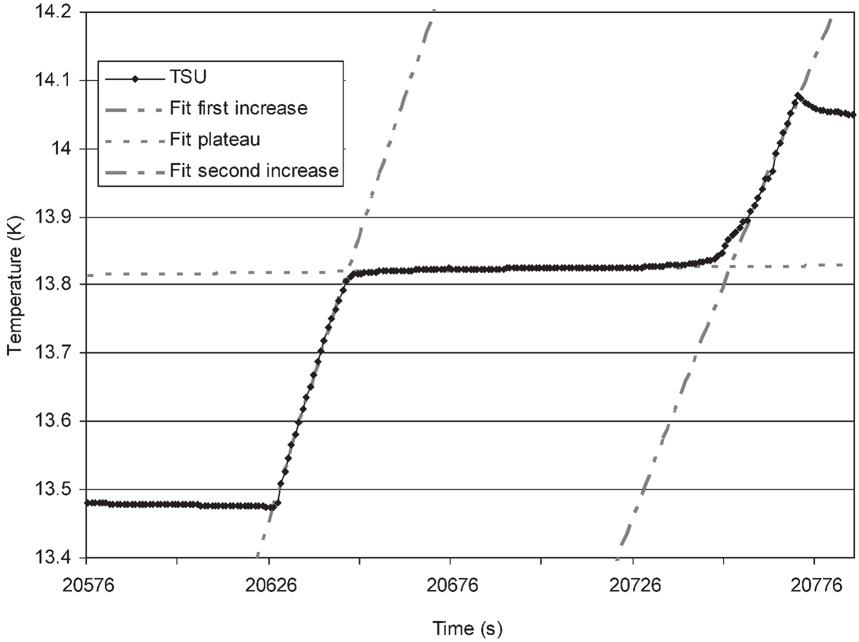

Figure 4. Thermal storage unit temperature evolution with an applied load of 100 mW.

the beginning and the end of the plateau by the intersections of the 3 fits described above and so, the duration.

For the thermal stability criteria, once the beginning and the end of the plateau is defined, it is possible using a fit of the data to define the temperatures at the beginning and at the end of the plateau and then the temperature drift that occurs along the plateau. It is also possible to use the slope (in K/s) of the linear fit of the plateau to give an indication of the thermal stability. In this case, the beginning and the end of the plateau determinations have no impact on the value.

Results

Different loads have been applied to the TSU. The duration of the plateau is plotted as function of the effective load applied in Figure 5. As the energy stored (E) is equal to the plateau duration multiplied by the effective load applied, a fit of E/load has been determined and is represented on the figure. The energy stored has been found to be 10.14 Joules which is in good agreement with the theoretical design value. A lower stored energy value found for the lower effective load could probably be attributed to the uncertainty on the thermal leak which strongly affects the estimation as the effective load is of the same order of magnitude as the heat leak.

The temperature difference between the beginning and the end of the plateau is plotted as a function of the effective applied load in Figure 6. As expected, this temperature difference increases with the effective load applied. This is due to the fact that the resistance of the thermal path between the heat and solid to liquid interface increase with time (increase of the liquid hydrogen film thickness and probably small modification of the thermal path into the copper bus). It should be noted that the temperature increase during the plateau is very low which demonstrates a very good thermal coupling with solid hydrogen. For 500 mW, the temperature increase is around 30 mK.

Test Against Gravity

The effect of gravity has been experimentally studied. In order to demonstrate that the liquid hydrogen will be confined during condensation and that the solid hydrogen will remain in close contact with the copper thermal bus, tests against gravity were performed. The test bench was put

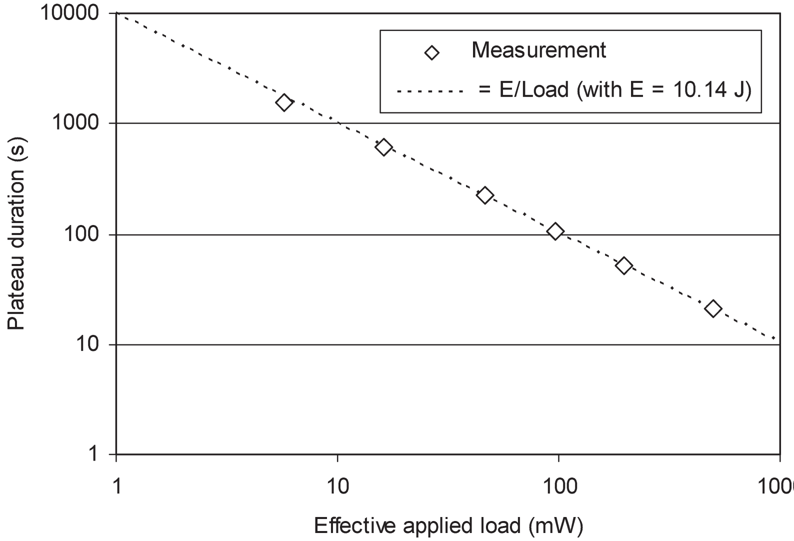

Figure 5. Plateau duration as a function of effective applied load

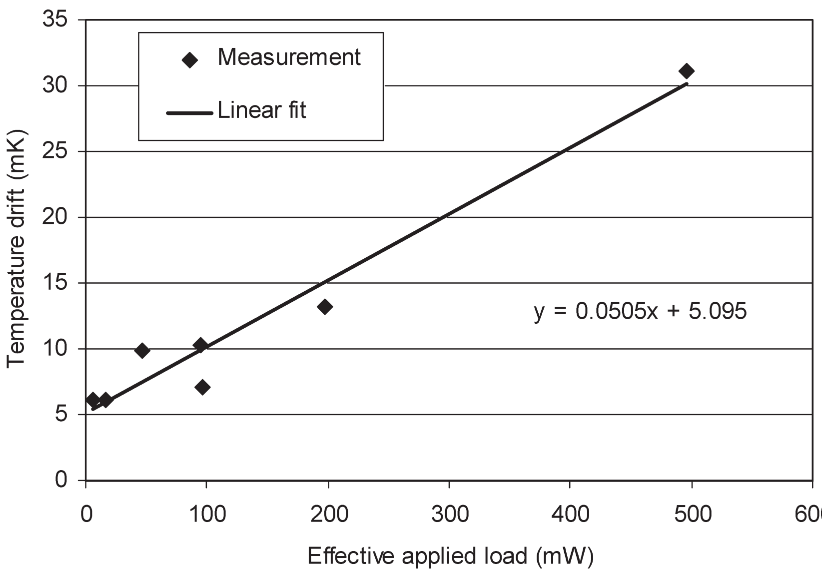

Figure 6. Temperature drift on the plateau as a function of the effective applied load

up side down, in such a way that the slots are open towards the bottom and the liquid could fall out of the thermal bus. Different loads have been experienced. For the first one, the cycle starts with all the hydrogen in the gaseous phase. The thermal bus was able to condense the vapor and confined the liquid hydrogen. Then, the liquid hydrogen was frozen and the solid hydrogen remained in the slots. This is demonstrated by the results obtained. The duration of the plateau as a function of the effective applied load is plotted in Figure 7 with one already obtained when the gravity is favorable to confine the hydrogen in the slots. There is a good agreement between the new points and the fit determined for the test when the gravity is favorable. For a higher effective load (1000 mW), the plateau duration seems to be overestimated. This is probably due to the fact it is difficult to determine with precision the duration of the plateau when the duration is very short (around 10 seconds

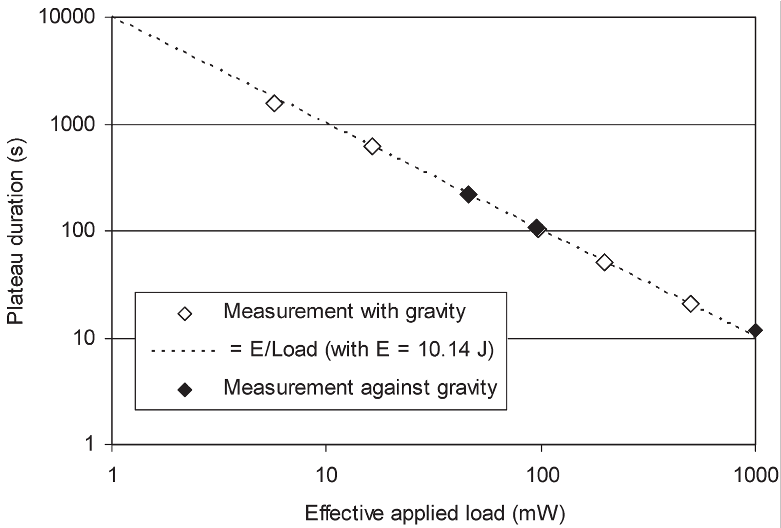

Figure 7. Plateau duration as a function of effective applied load

for the case described). Results are not shown in this paper but similar values have been found for the temperature drift with the cell unit upside down.

Single Volume Configuration Test

Finally a test has been performed in the single volume configuration. The cell was cooled and then isolated from the room temperature volume. Then, a 100 mW of load has been applied. The test results are compared in Figure 8 with one performed when the cold volume is connected to the room temperature volume. When the valve isolates the cold volume the pressure increases before (sublimation) and after (evaporation) the triple point is reached, leading to faster temperature increases. As expected, there is no significant difference for the plateau in terms of the duration

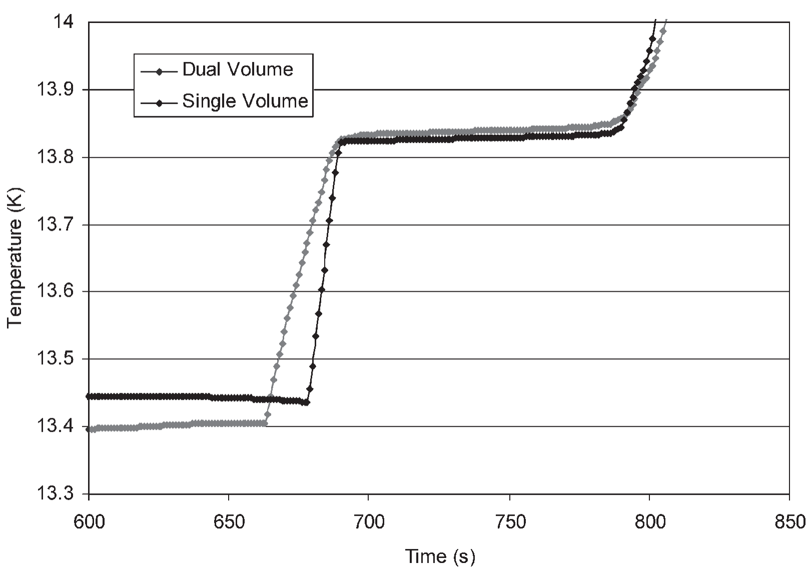

Figure 8. Temperature evolution in dual and single volume configuration, applied load 100 mW

(energy stored) or in terms of temperature drift. This demonstrates that experiments in the double volume configuration can be used to demonstrate the behavior of the cell in single volume configuration at the triple point.

CONCLUSION

A TSU using the triple point of hydrogen at 13.8 K has been designed and tested. Test with different heat loads have demonstrated that the energy storage value measured is in accordance with the design value. Due to the thermal bus design made of thin slots in copper, very low drift has been observed during the stable temperature phase corresponding to triple point. For 500 mW applied, a drift of 30 mK has been measured. A similar behavior has been verified when the cell unit is working against gravity which demonstrates the possibility to use this kind of cell for space missions. Potential applications will probably require a higher level of stored energy, and this prototype is thw first step that demonstrates the feasibility of using hydrogen at its triple point to adsorb peak thermal loads.

ACKNOWLEDGMENT

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