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Long term performance of vacuum insulation panels in hybrid insulation district heating pipes

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Abstract

This paper presents studies on district heating pipes where a vacuum insulation panel replace the innermost layers of polyurethane around the service pipe. One of the main challenges are their long term performance. Prototypes have been tested both in field in a district heating grid and in laboratory with a constant temperatures. The results indicate that the panels are intact after four years in field. In the laboratory, the pipes have been exposed to a constant temperature of 115°C for over three years without damage to the panels.

Peer-review under responsibility of the Scientific Committee of The 15th International Symposium on District Heating and Cooling.

Keywords: Type your keywords here, separated by semicolons ;

Nomenclature

COP	Center of panel
PUR	Polyurethane foam
VIP	Vacuum insulation panel

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1. Introduction

Statistics Sweden show that 10% of the energy input to the district heating network is lost as heat losses from the district heating pipes [1]. Reidhav and Werner show that the proportion of the losses might be even higher for areas with a less dense energy outtake [2].

IEA-DHC Annex VIII [3] suggests some different methods to reduce the losses by either changing the symmetry of the district heating pipes or arranging more pipes in the same casing pipe.

Dalla Rosa et al show that placing the supply pipe closer to the center of a twin pipe could reduce the losses by up to 3.2%. Further, Bøhm and Kristjansson [4] show that making the casing egg-shaped decrease the heat losses even more, by up to 7% compared to a circular twin pipe of the same size.

IEA-DHC Annex VIII [3] also suggests using high performance insulation close around the supply pipe. In a cylindrical geometry the effect of the insulation is larger, closer to the center of the cylinder. This is investigated in this paper.

1.1. Vacuum insulation panels (VIP)

Polyurethane foam (PUR), blown with carbon dioxide and some pentane isomers, is commonly used as insulation in district heating pipes. PUR district heating pipes are commercialized with a thermal conductivity in the range of 24-28 mW/(m·K) at 50°C [5]–[7]. This is in a similar range as that of researchers [8]–[10]. These values can be compared to vacuum insulation panels (VIPs), a new type of insulation for the district heating sector. With a fumed silica core the thermal conductivity at the center of the panels are as low as 4 5 mW/(m·K) as long as they are kept evacuated [11].

A VIP consists of a core material, commonly made of a porous silica structure, evacuated and encapsulated in a highly diffusion tight envelope, as shown in Figure 1. The envelope commonly consists of a laminate, alternating polymer layers and aluminium layers. The metal in the envelope creates thermal bridges along the edges of the panels which in turn creates an optimization problem. More aluminium in the envelope creates larger heat losses through the edges but reduce the diffusion of gas into the panels and thus prolongs the life span.

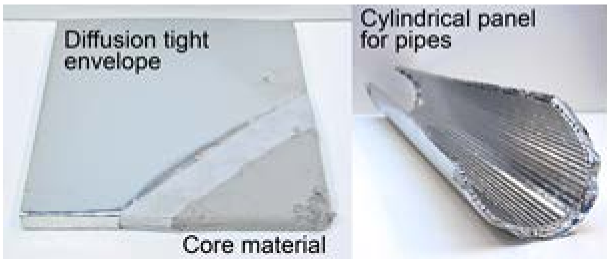

Fig. 1. An opened VIP to the left and a cylindrical VIP to the right.

The long term performance of VIPs have been investigated for building insulation by Simmler and Brunner [12] but in district heating the temperatures are much higher. Both Simmler and Brunner [12] and Schwab et al [13] show an exponential relation between temperature and rate of diffusion into the panels. Apart from the diffusion, the high temperatures of the district heating pipes might melt or damage the polymer in the envelope, leading to a fast deterioration.

1.2. Hybrid insulation

In a cylindrical geometry, the influence of the insulation is higher the closer it is to the center. This can be seen in the equation for heat flow through a cylindrical material layer, presented in Equation (1):

$$Q = \Delta T \cdot \frac{2\pi\lambda}{\ln(\Delta r / r_0 + 1)} \quad (1)$$

where Q [W/m] is the heat loss from the pipe, ΔT [℃] is the temperature difference over a material layer, λ [W/(m·K)] is the thermal conductivity, Δr [m] is the layer thickness and r0 [m] is the inner radius of the layer.

If the inner radius, r0, increases the heat flow increases for the same layer thickness. Also, the needed amount of material will increase with the square of the radius. This means that at a certain insulation thickness it will be cheaper to pay extra for a high performance insulation close to the center rather than to increase the thickness.

A concept for hybrid insulation district heating pipes have been under development through a series of research projects, where VIPs have replaced the innermost part of the insulation in a PUR pipe. The concept is presented in Figure 2.

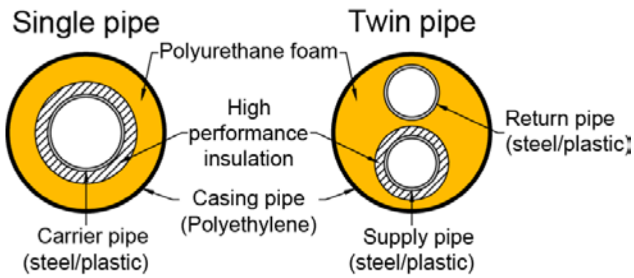

Fig. 2. Concept for hybrid insulation district heating pipes.

The heat losses have been measured through guarded hot pipe by Berge and Adl-Zarrabi for both single pipes [14], [15] and twin pipes [16]. The measurements on single pipes showed a reduction of almost 30% when a 10 mm VIP was added to a DN 100/225 pipe. The measurements also showed that a destroyed panel still had a thermal conductivity as good as that of PUR. For the twin pipes, a 10 mm VIP around the supply pipe reduced the total heat losses from a DN 2*80/315 by 12-18% depending on the overlap length of the panel. The losses from the supply water pipe was reduced even further by up to almost 40%.

The hybrid insulation district heating pipes have also been investigated through field measurements by Berge et al [17]. The paper presents a method to evaluate the long term performance of the vacuum panels through temperature measurements in field. The measurements showed that the panels are intact after three years of measurements. A slow diffusion might be present, but it can so far not be detected through the measurements.

This paper aim to summarize the measurements on the long term performance of hybrid insulation district heating pipes with vacuum insulation panels. The paper presents continuation of the field measurements by Berge et al [17], which have been active for another year. The field measurements are complimented by a new field measurements station and also by laboratory measurements of the long time performance.

2. Field measurements

Three pipe prototypes have been installed into field, connected to active district heating networks. The performance of the pipes have been monitored by continuous measurements of the temperatures throughout a cross-section of the pipes. The temperature have been measured with the use of type T thermocouples mounted before the PUR was added.

Two of the pipes were installed 2012 and connected to the district heating network in the city Varberg, a coastal city in south-western Sweden. Both were twin pipes with the dimensions DN 2*80/250 and DN 2*25/140. The measurement positions for the two pipes are shown in Figure 3. The temperature in every position was measured at least at two places along the pipe on two separate VIPs.

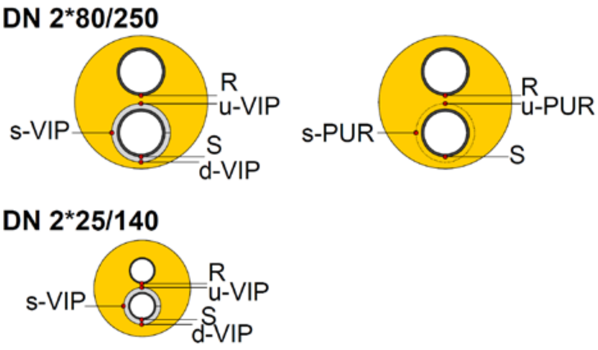

Fig. 3. The measurement position for the temperature measurements on the two twin pipes in Varberg.

The results from the field measurements in Varberg are presented in Figure 4 for DN 2*80/250 and Figure 5 for DN 2*25/260. The measurements show that there is typically low temperatures in the system, up to a max below 90°C.The results for both pipes are continuous with an apparent cyclic behaviour over the years. The temperature in the supply and return pipes seems to be at similar levels with the exception of the return temperature in Figure 4 which have decreased some over time.

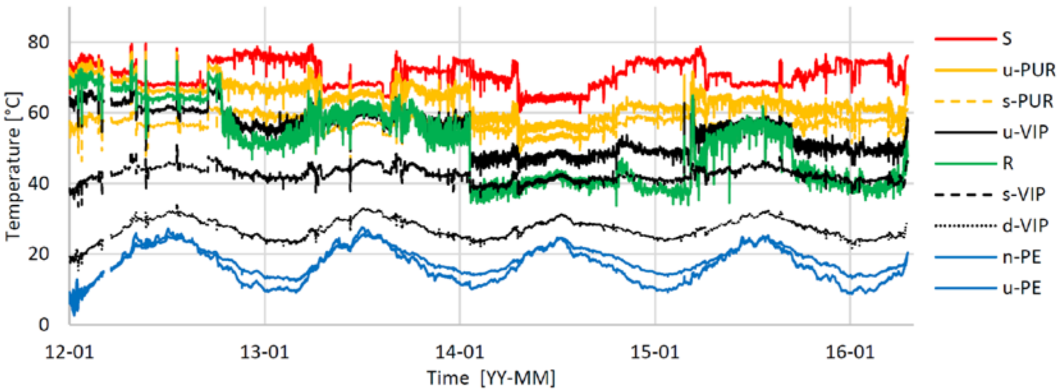

Fig. 4. Resulting averages for the positions of the pipe DN 2*80/250 in Varberg.

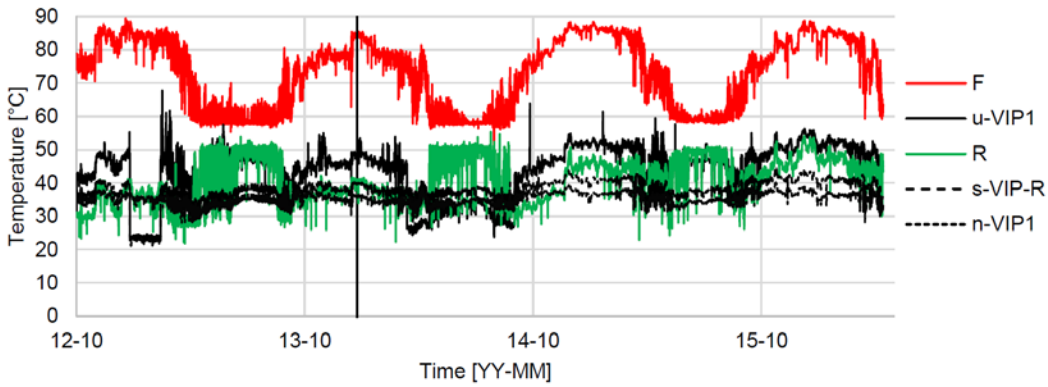

Fig. 5. Resulting averages for positions of the pipe DN 2*25/160 in Varberg.

In DN 2*80/250 the temperatures were measured in a reference part of the pipe without VIP. The measurements were made at corresponding positions to the measurements on the backside of the vacuum panels, in the middle of the polyurethane. In Figure 4 it can be seen that the reference points have considerably higher temperatures which is a sign that the heat flow from that point and out is larger in the reference. The VIPs show a direct result, lowering the temperature in the pipe.

The measurement results have been investigated by the error method by Berge et al [17]. The results are shown Figure 6 for DN 2*80/250. The result show a continuing slow change but still no alarming deterioration rate.

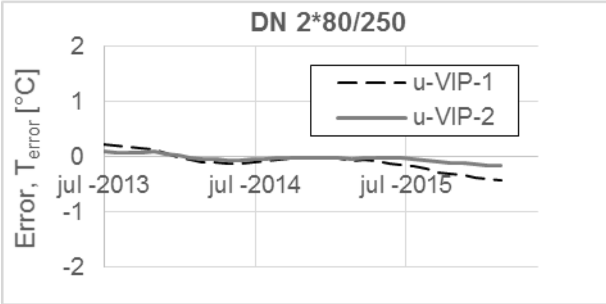

Fig. 6. Results for DN2*80/250 from the error model according to [17].

The third field measurement pipe is placed in the city Göteborg, also on the coast of south-western Sweden but a bit further north. The pipe was installed in the summer 2015 and the temperature was put on later during the fall. The pipe had the dimensions DN 150/280 and temperatures were measured on the backside of the VIP, on the service pipe and on the casing of the pipe.

The results from the measurements are shown in Figure 7.The single pipe in Göteborg contained four VIPs but when the pipe was installed, two of the VIPs were found to be broken (VIP 1 and VIP 2 in Figure 7), probably due to some mistake during production. This indicates another challenge with using vacuum insulation panels: how to handle them in production so that they are protected from injuries.

The measurements are just recently initiated so the long term performance of the vacuum panels can so far not be analysed.

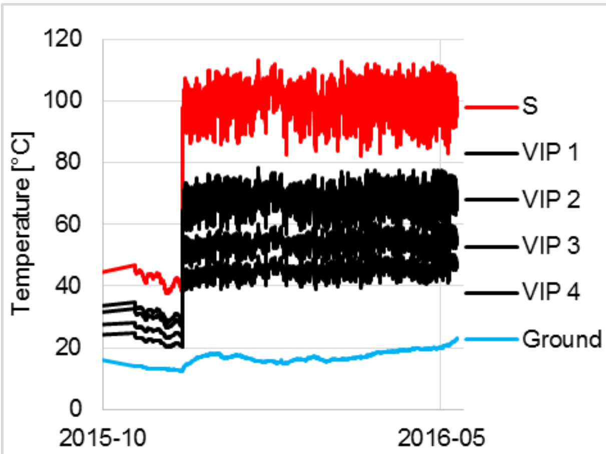

Fig.7. Resulting Temperatures in the pipe DN 150/280 in Göteborg.

3. Laboratory measurements

Single pipe prototypes have been investigated through long time measurements in the laboratory. Three hybrid insulation pipes were put in a rig with heated oil circulated through the service pipe. The temperature of the circulating oil was held constant and the temperature on the backside of the VIPs (center of panel, COP) and the temperatures at the envelope seals were monitored, together with the oil temperature and the casing pipe temperature. The rig is shown in Figure 8 together with a description of the temperature measurements.

Each pipe contained three 10 mm thick VIPs. The temperature in the pipe A, B and C was set to 115°C, 125°C and 135°C respectively. The measurements indicated that the VIPs were destroyed after 4 days at 125°C and instantly at 135°C. The measurements on pipe C was continued for 16 days and the measurements on pipe B was continued for 60 days. The measurements on pipe A is still ongoing after 3.5 years. The temperature levels for the last 15 days of measurement can be seen in Figure 9.

The seal temperature is investigate since it is assumed that the seals are a weak point in the envelope. During the production of VIPs, the seals are commonly closed by melting the two sides of the envelope together. A high temperature could thus open the seals again. Therefore, the seals where folded to the backside of the panels where the temperature was is lower. The results are shown clearly in Figure 9 where the temperatures in the seals are more than 30°C lower than the steel pipe temperature.

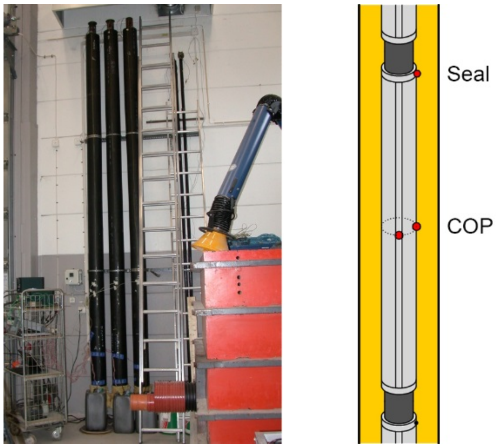

Fig. 8. Rig for high temperature measurements of hybrid insulation district heating pipes.

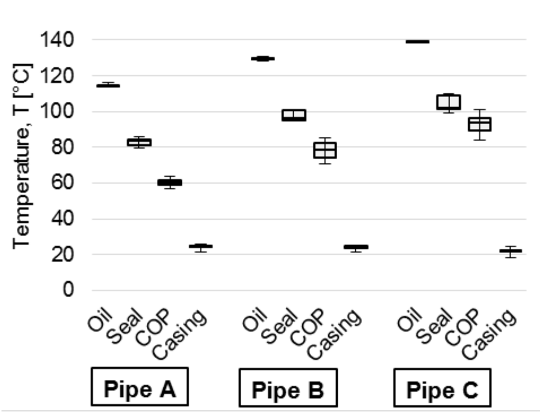

Fig. 9. Temperature measurements for the last 15 days for the three high temperature test pipes.

Allready in Figure 9 the temperature on the center of the panel (COP) in pipe A is proportionally closer to the casing temperature compared to pipe B and pipe C. This is a clear indication that the performance of the VIPs are better in pipe A compared to the polyurethane.

The temperature measurements for pipe A is shown in Figure 10. After 1.8 years, the measurements were turned off for some months but was reinitiated again and have been ongoing since.

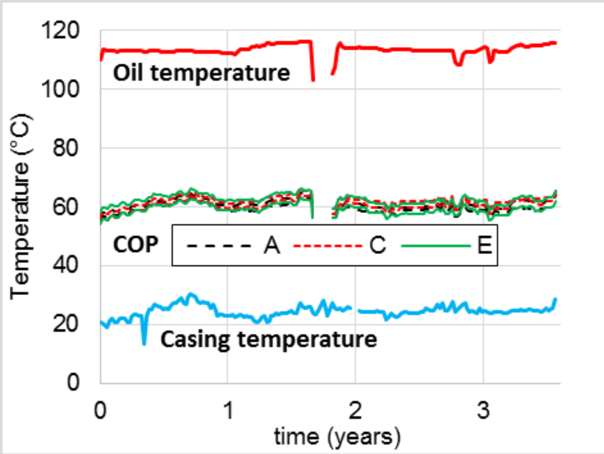

Fig. 10. Temperature measurements of Pipe A.

The performance VIPs can be investigated by how the temperature on the COP is proportional to the temperature on the casing and in the oil. The pipe can be seen as two cylindrical material layers one with VIP and one with PUR. By assuming a one dimensional, axisymmetric steady state heat flow out through the pipes, the temperatures can then be used to calculate the quotient between the thermal conductivity of the two layers, as in Equation (2):

$$\frac{\lambda_{PUR}}{\lambda_{VIP}} = \frac{\Delta T_{VIP}}{\Delta T_{PUR}} \cdot \frac{\ln(\Delta r_{PUR} / r_{0.PUR} + 1)}{\ln(\Delta r_{VIP} / r_{0.VIP} + 1)} \qquad (2)$$

where λ [W/(m·K)] is the thermal conductivity, ΔT [℃] is the temperature difference over a material layer, Δr [m] is the layer thickness and r0 [m] is the inner radius of the layers of PUR and VIP.

The results from the calculations of the quotients can be seen in Figure 11. At the beginning of the measurements, the thermal conductivity is around 3-5 times that of the VIPs. Seen both for pipe A and B in Figure 11. Panel E in pipe B stands out with a start quotient of 5. The large variation can otherwise be explained by the amplified effect of a shift in the temperature on the backside of the VIP. If the temperature is measured slightly wrong or there are inhomogeneities in the area around the thermocouple on COP, both the temperature differences in Equation (2) would change in opposite direction. Thereby, the change in the quotient get amplified. There could for example be a large air bubble outside f panel E in pipe B, making the thermal conductivity of the PUR locally lower, forcing up the quotient.

Pipe B in Figure 11 also show a clear deterioration of the VIPs where the quotient decrease with time at various pace for different panels. While VIP C and E show instant very fast collapses, VIP A slowly gets gas filled over a month.

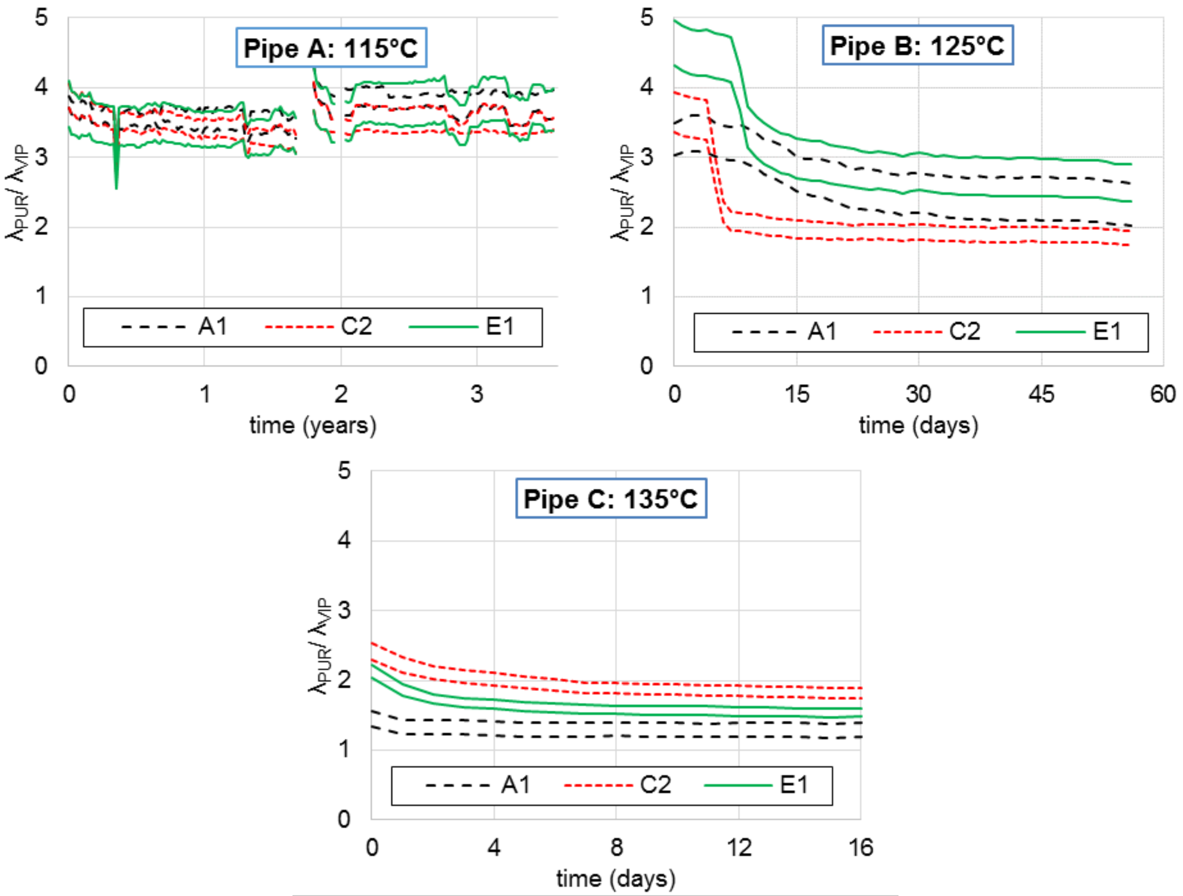

Fig. 11. Thermal conductivity quotient ($\lambda_{PUR}/\lambda_{VIP}$) for Pipe A, Pipe B and Pipe C (at different time scales).

For Pipe A there is no detectable change in the thermal conductivity quotient after more than three years of measurement. There is a small step change in the quotient when the experiment was reinitiated but this could be a consequence of a slight change in sensor placements on the casing. The method of using quotients are sensitive to small geometric changes due to large temperature gradients but should be consistent over time.

A quotient of three could be interpreted as a quite small difference since the presented properties of the PUR and VIPs are 26 mW/(m·K) and 5 mW/(m·K) respectively. On the other hand. The average temperature of the insulation will be influenced. The average temperatures of each material layer is presented in Table 1, showing a considerably higher temperature in the VIP than in the PUR which commonly give higher thermal conductivities for thermal insulations.

Table 1. Average temperature in the layers with VIP and PUR.

	$T_{avg\ VIP}$ [°C]	$T_{avg\ PUR}$ [°C]
Pipe A	88	43
Pipe B	104	51
Pipe C	116	57

It is important to note that the quotient is over 1 and for some cases almost three, even when the panel is considered destroyed. In 20°C air, fumed silica have a thermal conductivity around 21 mW/(m·K) [11]. But this could be lowered if the surrounding gas consists of carbon dioxide and pentane isomers.

4. Conclusions

The measurements presented in this paper show promise for hybrid insulation district heating pipes with VIPs. After four years in field the vacuum in the VIPs are still intact.

The same goes for the vacuum panel which have been continuously exposed to 115°C for more than 3 years. There is still no sign of deterioration.

When the temperature reaches above 125°C the VIP starts to deteriorate fast and the VIP seems to be gas filled in a couple of days. When the temperature reached over 135°C, the damage was instant.

In the applications the VIPs showed a thermal conductivity 1/5 to 1/3 of that of the PUR. But the average temperature in the VIPs are high. Since the VIP has a lower thermal conductivity than the PUR it will actually lower the temperature in the PUR and thus improve its thermal conductivity.

The damaged VIPs still showed a considerably better thermal conductivity than the PUR.

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