From: Proceedings of the 9th International Vacuum Insulation Symposium, London, 17th-18th September 2009.
http://www.ivisnet.org/

A PARAMETRIC FEASIBILITY STUDY ON ACTIVE VACUUM INSULATION PANELS FOR BUILDINGS

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Conference Theme: VIP Performance – Optimisation, Testing, and Modelling

Key Words: Active, Feasibility, Modelling, Optimisation, Building Physics

Abstract: The UK construction industry is moving towards better-insulated zero-carbon buildings. A new generation of wall insulation is required in order to achieve high insulation levels within an economical wall thickness. One approach is to transfer technology used in the refrigeration industry, wherein a partial vacuum is applied to a closed cellular construction. In this way robust evacuated panel-like elements of insulating material can be supplied to site for rapid installation. Such a system may also provide scope for actively evacuating and de-evacuating the panel elements to meet the diurnal and seasonal requirements.

This paper describes an initial parametric study for an active vacuum insulated panel (aVIP). The study is based on a specially developed analytical model that describes the heat transfer (via the four separate modes of solid conduction, gas conduction, gas convection, and radiation) and the structural behaviour of an aVIP. The predictions obtained from the analytical model are validated against data from experimental investigations on a typical panel.

The analytical model is subsequently used for performance-based design optimisation of the aVIP. This is achieved by performing materials selection for the panel and core using merit indices to select low-cost materials with good thermal and mechanical properties. The analytical model is then used to optimise the structural and thermal performance over a range of design parameters, and to determine whether the target conductivity of 4mW/mK can be achieved under expected operating conditions.

The experimental test results established confidence in the model and its key finding: that heat transfer across an open cellular panel is unacceptably high (140mW/mK at 14mbar) without a porous filler material in the core. The model predicts that it is possible to achieve a conductivity of 6.4mW/mK at 2mbar, which despite missing the ambitious target of 4mW/mK indicates that active high performance panels are feasible. The findings from the initial economic comparison are used to develop a conceptual design specification, but further numerical modelling is now required to fully validate the analytical model and to investigate issues such as permeation and outgassing. It is hoped that the findings of this initial study, particularly the analytical model developed, will help guide further research in the area.

1. INTRODUCTION

1.1 The growing need for shrinking insulation

In recent years, concerns about energy efficiency in buildings have led to stricter requirements for building insulation U-values. As this trend continues in the UK and elsewhere, it will soon become unfeasible to continue using thicker and thicker layers of existing foam and fibre insulation. This is a result of various factors: material cost of insulation increasing with thickness of layer; more complicated design and more expensive construction due to thicker walls or cavities (thicker wall ties, deeper door and window reveals, etc.); loss of usable/saleable floor space as insulation layers cause walls to encroach into building interior; and less aesthetically pleasing buildings (thicker external walls reducing daylight penetration and architectural expression).

As regulations become stricter, minimum thicknesses rapidly become a problem, especially for cavity wall construction, which accounts for many domestic and commercial buildings in the UK. Figure 1 shows the effect of minimum U-values on wall thicknesses for a range of traditional and advanced insulants, as the U-value is decreased from the current UK requirement of 0.3W/m^{2}K to 0.1W/m^{2}K as suggested in the Code for Sustainable Homes (DCLG, 2008).

A new generation of insulant will be required which combines low cost with low conductivity for thin, high-performance building insulation. In order to determine the specification for such a product, a typical British dwelling was considered using nationally averaged data for floor space and house price. A target conductivity of 4mW/mK within 40mm thickness was applied, to achieve a U-value of 0.1W/m^{2}K.

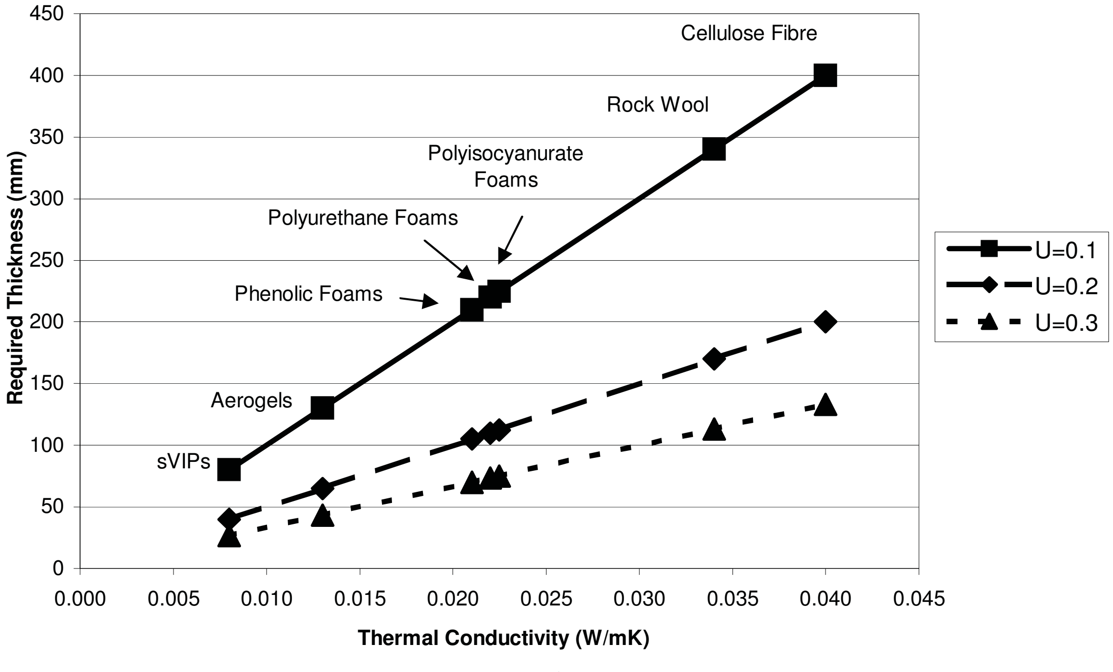

Figure 1: Insulants' conductivity vs. thickness required for target U-value

It is clear that as U-values decrease, advanced materials such as static Vacuum Insulation Panels (sVIPs) will become more attractive compared to foam and fibre insulants, with higher material cost outweighed by space-related savings.

1.2 Active Vacuum Insulation Panels

At the time of writing, typical commercially available static vacuum insulated panels (sVIPs) have a service life of only around 20-40 years. Over time, permeation and outgassing degrade the vacuum, raising the panels' conductivity. In cavity wall construction, the insulation must have a design life of at least 100 years to match that of the building. One possible solution to this engineering problem is to incorporate a system for active, periodic re-evacuation to combat the inevitable permeation and outgassing. These active VIPs (aVIPs) have a potentially indefinite design life, and may even allow the active 'tuning' of the building envelope on a seasonal basis to control heat gains and losses.

This paper describes an initial parametric study into this type of panel. An analytical model is developed to predict the thermal and structural behaviour of a particular panel design. The results are used to create merit indices to help material selection. Several design parameters are then varied to predict trends and optimise panel performance over the entire service life. The performance trends as predicted by the model, as well as the model itself, are intended to act as a tool to aid further design work. More validation, testing, and refinement of the model are required, for example inclusion of specific effects such as permeation of water vapour, which may strongly affect panel performance and pumpdown capability.

2. THE ANALYTICAL MODEL

2.1 Structural Modelling

The panel was initially modelled as an infinitely long, regularly repeating prismatic box section under a pressure load of 100kPa (perfect internal vacuum). Panel faces were given a stiffness constraint (maximum deflection under load) and strength constraint (stress not to exceed the design strength), whereas side ribs were similarly assigned buckling and crushing failure constraints. These sets of constraints were used as a subroutine in the model to calculate minimum member thicknesses for a given panel geometry and material.

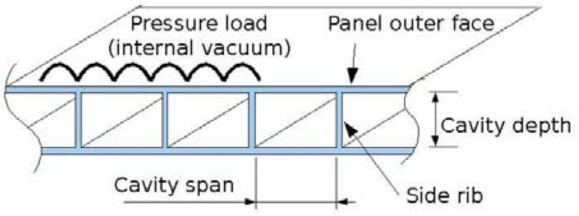

Figure 2: Panel geometry

2.2 Thermal Modelling

The thermal modelling was performed in four parts. An effective U-value was obtained for each of the four modes of heat transfer: solid conduction, gas conduction, gas convection and radiation. At this stage the contribution due to mode interaction was neglected. For the initial panel design, a total U-value was hence obtained, and this process along with the structural modelling formed the model's main loop to be used later for optimisation. The process was repeated while varying input design parameters, in order to investigate trends and optimise the design, as mentioned in Section 1.2.

2.2.1 Gas Conduction

The variation of gas conductivity with internal pressure as described by Kaganer (Kaganer, 1969), was used to determine gas conduction between the panel's inner faces. It was found that with an open cavity, the internal gas conductivity did not reduce appreciably from its atmospheric value, within the range of rough to medium vacuum considered to be practically achievable (minimum pressure around 2mbar or 200Pa). Since this would cause heat transfer due to gas conduction alone to greatly exceed the overall target of 4mW/mK, it was necessary to fill the panel core with a fine porous material. The smaller characteristic distance between pore walls would cause the gas conductivity to reduce at higher threshold pressures – the Knudsen effect – as shown in Figure 3. This finding agrees with Simmler et al.: “nano-structured materials require the least quality of vacuum, which has to be achieved and maintained” in order to maintain low gas conductivity (Simmler et al. 2005)

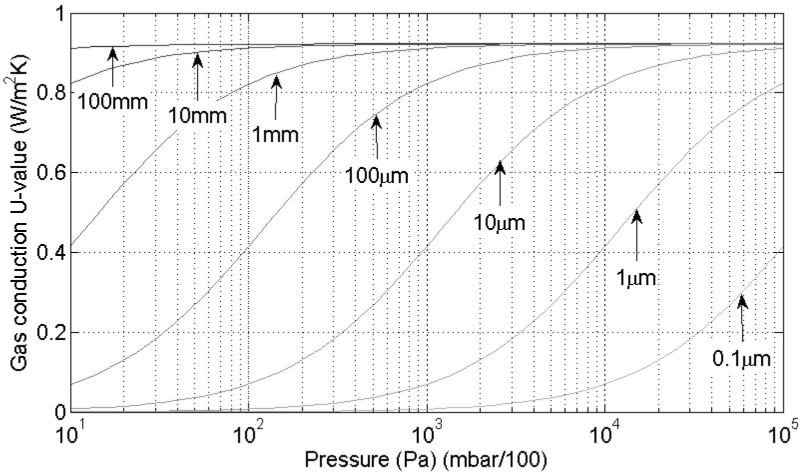

Figure 3: U-value (gas conduction only) of a partially evacuated air-filled panel of 28mm width

2.2.2 Solid Conduction

The contribution from solid conduction was treated as a simple 1D case, since the panel side ribs were of constant cross sectional area and ran parallel to the temperature gradient. The numerical modelling performed so far indicates that this is a valid assumption - the total effective conductivity of a section of this type was predicted to be a fraction of the solid conductivity of the material used, the fraction being equal to the rib thickness divided by span between ribs. Lines of constant temperature remain roughly parallel to the outer panel faces, which compares well with the findings of Bundi et al. (Bundi et al., 2003); hence solid conduction is treated as 1D.

2.2.3 Radiation

Standard formulae for radiation, view factors etc. across an open rectangular cavity were taken from Incropera et al. (*Fundamentals of Heat and Mass Transfer*, Incropera et al., 2006). In the case of the core being filled with porous material, the effect of the porosity was approximated by a regular cubic closed lattice of cell size equal to the pore size being considered. By assuming 1D radiative heat flow across the panel (i.e. in each individual cell, the only net heat flux was across the walls normal to the temperature gradient, and the flux through all cells was equal) and applying an overall temperature difference of 20°C (as per ISO 8990 regulations on guarded hotbox testing of insulants), an iterative approach was used to obtain both the internal temperature profile and total heat transfer. Since the total temperature difference of

20K was much smaller than the absolute temperatures of 273 to 293K used, the temperature profile obtained was close to linear. As the conductive temperature profiles were also linear, and the non-linear convection term became insignificant once a porous filler had been introduced, it seemed reasonable to neglect the interaction between different heat transfer modes in the model.

2.2.4 Gas Convection

Empirical correlations for gas convection across a rectangular cavity were taken from Incropera et al. (*Fundamentals of Heat and Mass Transfer*, Incropera et al., 2006) with modified fluid properties according to the reduction in internal pressure below atmospheric. The effect of a porous filler on convection was modelled in the same way as radiation, by treating the filler as a regular cubic closed cellular structure, and using empirical calculations to calculate convection between the hot and cold faces of each cell.

3. MATERIAL SELECTION AND OPTIMISATION

3.1 Material Selection

The equations used to obtain minimum section thicknesses for the panel structure were then used to aid material selection. For example, by varying the span of the initial panel design it was found that buckling of the panel's side ribs was the dominant failure mode over most of the acceptable range (span 0 to 260mm) and was the active constraint at the point of minimum solid conduction heat transfer (210mm). The minimum thickness of the side ribs was found to be proportional to $E^{1/3}$ (where E is the material's Young's Modulus). Hence that the material with the highest value of $E^{1/3}/\alpha$ (where α is the thermal conductivity) will perform best, since the side ribs will be both thin and poorly conductive, minimising heat transfer while sustaining the pressure load. This performance index was used with a materials selection chart to find that PMMA was one of the best performing materials in this regard (materials such as polymer foams, paper, cardboard and bamboo had higher indices of $E^{1/3}/\alpha$ but were rejected at this stage in favour of PMMA as this is simple and relatively inexpensive to manufacture in custom shapes, in large volumes and with high precision. Later, these other materials can be considered if higher performance is required from the panel material.

Material selection for the core filler was performed by identifying a pareto-set of open-cell foams with low cost and low thermal conductivity. Polyurethane (PU) elastomeric open cell foam was chosen as it had the lowest conductivity and reasonable cost per unit volume.

The quoted conductivity of PU open cell foam, chosen as the filler material, was over 24mW/mK, much higher than the panel's overall target of 4mW/mK. However, insulants are not usually evacuated before guarded hot box testing according to ISO 8990, and at atmospheric pressure and with the typical pore size of PU foams of 250μm or greater, the Knudsen effect is not present and the conductivity of air is not reduced from its normal value of 25.1mW/mK. It is hoped that the conductivity of the air trapped inside during testing dominates the total measured conductivity of the foam. By evacuating the core, the conductivity should be greatly reduced, the contribution due to solid conduction through the walls of the foam being small due to its low volume fraction and highly tortuous paths of heat transfer. More numerical modelling and testing will be required to validate this.

3.2 Optimisation

3.2.1 Span Length

The first parameter to be varied was the span between the panel's supporting side ribs, as mentioned in Section 3.1. It was found that a significant reduction in solid conduction through these ribs could be achieved by increasing the span from the original 30mm, to between 100 and 200mm. As the span increases, so does the pressure load transmitted through compression in the ribs, meaning each rib needs to be thicker and hence will transfer more heat. However, as the span increases these thermal bridges become more widely spaced, and so the total heat transfer per unit area actually decreases. A third issue is that the stiffness constraint on panel faces means that with wider spans the faces also need to be thicker, and so for a fixed total panel depth the effective length of the ribs decreases. This means that the minimum rib thickness to prevent buckling actually decreases once the span increases beyond a certain threshold value (which depends on the material used). This effect is only observed if the buckling constraint determines rib thickness rather than the strength (crushing) constraint, but this is the case for all materials so far considered. Figure 4 shows the variation of total heat transfer per unit area as a function of span length. Heat transfer is reduced in three ways: by increasing the panel depth to 40mm; changing material from the initial uPVC to PMMA; and increasing the span from 30mm.

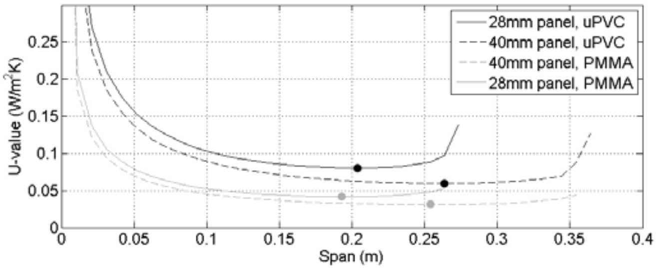

Figure 4: U-value of solid conduction through ribs, with varying span length

Some rise in internal pressure over the panel's service life will be unavoidable, and the panel should be designed to work well at higher than the initial pressure. As the span length increases, so does the minimum face thickness, and the internal cavity depth is reduced. A perfect vacuum (zero gas conductivity in the cavity) favours a wider span since the only thermal bridges are the widely spaced and thin side ribs. However, once rising internal pressure increases gas conductivity, the cavity itself becomes a better pathway for heat transfer. Shorter spans and deeper cavities become more favourable. Figure 5 shows the total solid and gas conduction as pressure rises.

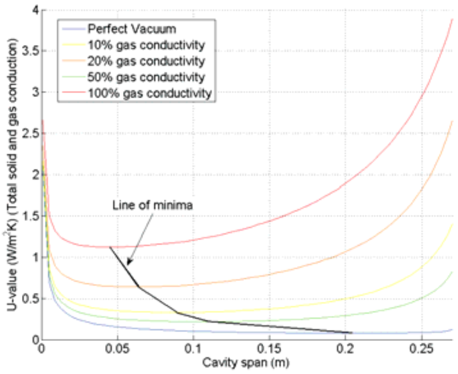

Figure 5: Total conduction vs. gas conductivity and span length

While a span of 206mm minimises solid conduction, the depth of the internal cavity for this span length is small, such that any rise in gas conductivity leads to a considerable increase in total heat transfer. With a shorter span (and hence a deeper cavity) the design is clearly more robust, with slightly higher solid conduction but much higher resistance to increases in gas conductivity due to loss of vacuum.

3.2.2 Pore Size

As shown in Figure 3, a core material with smaller average pore size will help to reduce heat transfer by gas conduction via the Knudsen effect. A pore size of between 1 and 10µm will reduce the conductivity of air at a design pressure of 2mbar to less than 15% of its atmospheric value, to approximately 4mW/mK or less.

By introducing a filler of this pore size, the model predicts that radiation is reduced effectively to zero (see Figure 6). This result will need to be validated with testing and numerical modelling, but if true will mean that only gas conduction will need to be considered in future when determining pore size.

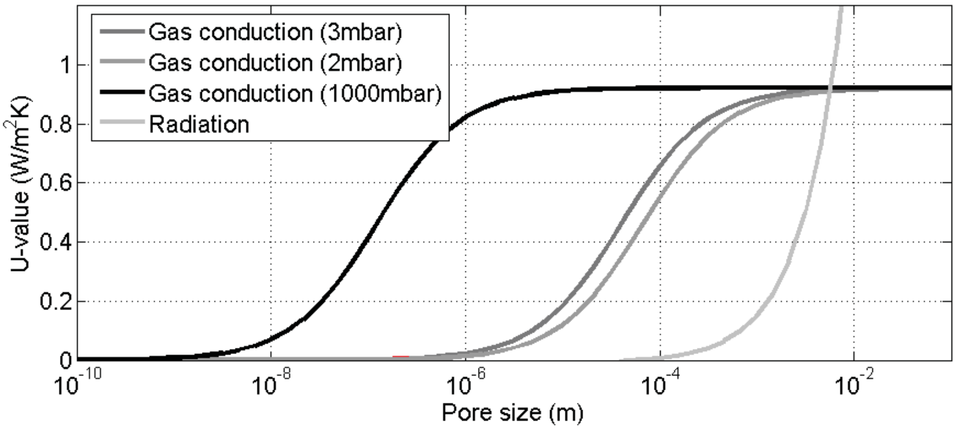

Figure 6: Radiation and gas conduction of 28mm panel at design and atmospheric pressure

The model predicts that in the case of an open cavity convection is negligible below a pressure of 200mbar, and rises to a maximum of around 8.0W/m^{2}K. However, it also predicts that when a filler material is introduced, this does not change significantly. This seems unlikely, since foam and fibre insulations work by impeding convective currents due to their small (mm-µm scale) microstructures. The model will have to be refined to accurately predict convective losses, but for now convection is assumed absent with a 1 to 10µm scale filler material.

4. ANALYTICAL RESULTS AND EXPERIMENTAL VALIDATION

4.1 Initial Panel

For the initial design considered (28mm panel, 30mm span length, uPVC panel with open cavity), the model predicts a constant U-value of 5.3W/m^{2}K (effective conductivity 149mW/mK) over a wide range of internal pressures between 0.2mbar and 200mbar. This is mostly due to radiation at 4.1W/m^{2}K, although solid and gas conduction both individually account for more than the overall limit of 0.1W/m^{2}K. As pressure rises further, convection dominates and causes the total heat transfer to rise, to a maximum of 13.3W/m^{2}K.

4.2 Experimental Validation

The work undertaken so far has been mainly theoretical: creating the analytical model; using it to explain the interrelationships between the various parameters; and performing some optimisation to obtain an estimate of the minimum achievable conductivity. For validation, we relied on experimental testing performed by CERAM Research on behalf of the Modern Masonry Alliance (MMA), who shared the results of the testing. This consisted of a uPVC panel identical to the initial design considered in this project, which was tested in a guarded hot box at 14mbar. The measured conductivity was 140mW/mK, with an error margin of ±15% due to the difficulty of testing a single panel. The model's predicted value of 149W/mK at this pressure is well within this error margin.

The agreement of the experimentally determined and predicted U-values is encouraging. However, more testing will be required in order to validate the model's predictions of panel behaviour with changing parameters, particularly with the addition of a porous filler material.

4.3 Minimising Heat Transfer

4.3.1 Gas Conduction

As the conductivity of air and water vapour are both greater than the target conductivity of 4mW/mK, a porous core material must be inserted into the panel cavities to reduce the conductivity to an acceptable level at an achievable pressure. It has been shown that by introducing a filler of pore size between 1 and 10µm, gas conductivity can be reduced to around 4mW/mK. Reducing the pore size will increase the threshold pressure at which the gas conductivity begins to rise, and hence will make the panel's overall U-value more resistant to rising internal pressure. However, reducing the pore size will also make the process of re-evacuation more time and energy intensive. It is also unknown whether PU foam can be manufactured with such a low pore size, since it is commonly manufactured with pore size 250µm or greater.

4.3.2 Solid Conduction

Through materials selection, increased section depth from 28mm to 40mm, and optimisation of span length, the total conduction across the panel side ribs was reduced from 0.32W/m^{2}K to 0.03W/m^{2}K. By introducing a porous filler material to the cavity, an extra solid conduction term was introduced. More testing is required to determine the solid conduction of the core material. This will be less than or equal to 24mW/mK, but as discussed in Section 3.1 the value is expected to be much lower than this.

4.3.3 Convection and Radiation

It is expected that the fine porous filler inserted to reduce gas conduction will also greatly reduce convection and radiation, so that these can be neglected. However, more testing is required to validate this assumption.

5 CONCLUSION

5.1 Work completed

So far, the project has been successful in developing a simple analytical model to predict the thermal and structural performance of a simple vacuum insulated panel. The accuracy of this model has been validated for one data point. The model has been extended to include a porous cavity filler material. Preliminary materials selection on the panel and core material has been performed. The model has been used to explore the dependence of thermal and structural performance on various parameters, and to optimise the design to minimise heat transfer. This has been successful, with a predicted total conductivity of between around 5mW/mK and 29mW/mK depending upon gas conduction and solid conduction through the core. Despite missing the ambitious target of 4mW/mK, this indicates that high-performance insulation is possible within 40mm thickness.

5.2 Gaps and future work

In order to test the feasibility of an actively pumped vacuum insulation system, the rate of increase of pressure over time must be investigated. So far, it has been assumed that the performance of available static vacuum insulation panels (va-Q-tec *va-Q-vip B* panels, initial pressure of 2mbar, rate of rise of 0.1mbar/year). However, this performance may not be achievable, due to outgassing from panel materials, permeation through the re-evacuation system itself, and other factors. The achievable rate of rise of pressure must be found in order to determine the pore size of filler, and re-evacuation system and schedule, required. In particular, since the water vapour transmission rate may be up to 1000 times greater than that of oxygen or nitrogen (Simmler et al., *HiPTi Subtask A Report*, 2005) investigating the effect of water vapour on permeation and re-evacuation should be a priority.

More testing will be required to validate the model for different data points. Any discrepancies will be investigated and used to refine the model. As a proxy for experimental testing, numerical modelling may be performed with a simulation package such as ANSYS, Abaqus or TRISCO.

6 ACKNOWLEDGEMENTS

Special thanks to:

Lauren Anderson and Geoff Edgell, CERAM Research
Michael Driver, Martin Clarke and Mike Leonard, Modern Masonry Alliance
Ian Abley, Loughborough University

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