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Why and Which Insulation Materials for Refrigerators!

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ABSTRACT

Transmission is the major contributor (> 50%) to the total cooling load for typical domestic refrigerators. Understandably, insulation in refrigerator walls plays an important role in reducing it. In the present work, a system level computer model of domestic refrigerator has been developed and the effect of different insulation materials, with varying thickness, on the energy consumption, weight, inner-volume and payback periods investigated. The insulation materials studied include polyurethane (PU) foam and vacuum insulation panels (VIPs) made with fumed silica, glass fibre and alternative core materials. Optimum thickness of the insulation material for fridge and freezer were identified through a parametric sweep with an objective to minimize payback period.
A fumed silica VIP insulated refrigerator is predicted to consume around 20% lesser energy over its lifetime, yield 148 litres extra storage volume and offer a payback period of 3 years relative to PU foam insulated refrigerator. Glass fibre VIP insulated refrigerator was found to have no payback because of their increased thermal conductivity due to ageing.
Keywords: Vacuum Insulation Panels, Energy Efficiency, Insulation Comparison.

1. INTRODUCTION

Refrigeration consumes about 6% of the total energy generated in the world and accounts for about 14% of the total household energy consumption (Melo & Silva, 2010). More than 50% of the thermal load in a refrigerator is caused by heat gain from the walls (ASHRAE, 2006). Insulation, thus have a significant effect in reduction of overall energy consumption of a refrigerator. Due to its low thermal conductivity, low cost and light weight, polyurethane foam (thermal conductivity = 21-25mW/mK) has been widely used as the insulation material for refrigerators since 1960s and till date it's the most popular insulation. Does that mean there isn't much scope of improvement in insulation materials?
Vacuum insulation panels (VIPs) can achieve a thermal conductivity as low as 3mW/mK (7 times lower than PU foam) (Alam et al., 2011). VIPs are three phase systems comprising of an evacuated core, mixed with additives such as getters and opacifiers, sealed in an envelope. The thermal conductivity of a VIP depends upon a range of factors including materials, operating temperature, sealing pressure etc.
VIPs are being identified as the potential next generation thermal insulation for various cold chain equipment including refrigerators, freezers, vaccine boxes, reefer trucks etc. Thiessen et al. (2016) reported a 21% reduction in energy consumption when 56% of the refrigerator area was covered with glass fibre VIPs. Hammond et al. (2014) calculated a payback period of 9.7 years when it was insulated with VIPs with thermal conductivity of 4 mW/mk. Tao et al. (2004) reported an 11.1% reduction in energy consumption by installing VIPs in side walls of a display case refrigerator. None of the above study analysed the effect of ageing on thermal conductivity, which can significantly change results.
In the present study, transmission load was calculated for refrigerators with various insulation materials. A parametric analysis was performed to find the optimum thickness of fridge and freezer insulation material with an objective to reduce the overall cost incurred during the lifetime of the refrigerator. The different materials with optimum thickness were then compared on the bases of life time energy consumption, insulation weight, inner volume and payback periods.
The rise in demand of VIPs have led the way to innovations in manufacturing. As of now, VIPs of sizes as large as 1.2m x 1.8m and of various geometrical shapes, including cylindrical shapes are available. In this study, it has been assumed that VIPs of any required size and shape to be fitted in the walls of refrigerator are available.

2. METHODOLOGY

2.1. Geometry

A 450-litre bottom-freezer refrigerator geometry with dimensions 2150mm x 762mm x 610mm (H x W x D) was modelled in COMSOL Multiphysics (Figure 1). Rate of heat gain in the refrigerator was numerically solved for using the heat transfer module. Convection boundary conditions (inside and outside the refrigerator) were used as prescribed by ASHRAE guidelines (Table 1) (ASHRAE, 2006) and the temperatures were in accordance with the study conducted by Biglia et al., (2018). The geometry was meshed using custom mesh (element size: 172 mm to 8.6 mm) made of free tetrahedral elements. Total number of mesh elements solved for was 1039660.
The refrigerator compartment was modelled as a three phase system consisting of an outer metal shell, (0.5 mm thick), an inner plastic lining made of PVC (2 mm thick) and an insulation material (variable thickness) sandwiched between the metal sheet and the plastic liner (Figure 1(b)). Different insulation materials (table 2) were employed and their effects analysed based on energy and physical change.

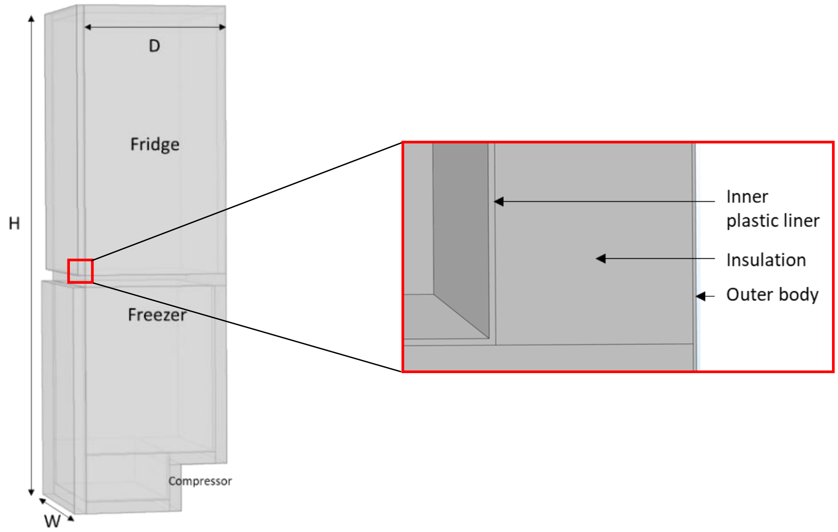

Figure 1: Refrigerator geometry a) full (semi-transparent) b) enlarged view of side wall without the door

Table 1: Boundary conditions used in the computer model

	Heat transfer coefficient (W/m^{2}K)	Temperature (°C)
Inner walls – Fridge	1.3	5
Inner walls – Freezer	1.3	-20
Outer walls (excluding compressor)	1.3	25
Compressor walls	6	30
Evaporator wall	(Constant temperature)	-20

2.2. Materials

Four different insulation materials were studied for their effect on refrigerator performance (Table 2). Rigid polyurethane foam (PU foam) is the most common insulation material for cold chain equipment. Cyclo-pentane filled PU foam was used for this study. Vacuum insulation panels with cores made of fumed silica and glass fibre are commonly available. Glass fibre VIPs offer low cost and excellent initial thermal conductivity which rises rapidly with time; a major shortcoming that has hindered its reliable market acceptability. On the other hand, fumed silica VIPs have lower density and a low thermal conductivity, with a gradual increase over time. Due to cost and strength considerations, fumed silica VIPs haven't yet found much wide acceptability either. A large portion (around 60%) of the total VIP cost is the material cost and thus it is safe to assume that volumetric cost of VIPs is constant. A lot of research is focused on development of composite core materials to lower the overall VIP cost and improve VIP strength (Singh et al., 2015), (Alam et al., 2014). An example is a composite core material formed with expanded perlite and polyester fibres developed by Alam et al. (Alam et al., 2014) which resulted in a cost reduction of 20% of the core.

Table 2: Materials employed in the research

Insulation material	Identifier	Initial thermal conductivity (W/mK)	Density (kg/m^3)	Cost (£/m^3)
PU Foam	M1	0.0215	80	950
Fumed silica VIP	M2	0.0037	200	2390
Glass fibre VIP	M3	0.0029	250	1800
Alternate core VIP	M4	0.0076	220	2000

2.3. Thickness of insulation materials

The rise in insulation thickness lowers the energy consumption due to decreased U-value but results in higher initial equipment cost due to increased volume of insulation material being used. In order to determine the optimum thickness of insulation materials, which offers both low energy consumption and low initial cost, a parametric study was performed. The thickness of insulation material in the fridge and freezer was independently varied in the range of 10 mm to 50 mm, keeping the outer dimensions of the refrigerator constant and thermal transmission load with time was evaluated at each step. The transmission load was converted to cumulative energy consumption over the life time of 13 years and total cost of electricity (for 13 years) was calculated assuming a constant rate of 0.125 £/kWh i.e. the present rate (UK Power, 2019). The energy consumption was then converted to equivalent CO_2 emissions for UK, considering an emission factor of 0.3072 kgCO_2e/kWh, including generation and transmission of electricity.
The data obtained was plotted in the form of 3D surfaces with the insulation thickness of fridge on x-axis, insulation thickness of freezer on y-axis and a cost function for resulting geometry on the z-axis. Cost function (CF; in £) was defined as the sum of total electricity cost over the lifetime of refrigerator (EC; in £) and the initial insulation material cost (IC; in £). Cost of various insulation materials employed in the study are given in table 2. The point of minimum cost function was considered the optimum thickness of insulation.

$$CF = EC + IC \quad (1)$$

2.4. Thermal conductivity of insulation materials

Thermal conductivity of cyclo-pentane filled rigid polyurethane foam is reported to be 0.0215 W/mK. Present blowing agents like cyclo-pentane (k = 12.8 W/mK) and CO2 (k = 16.6 W/mK) have higher diffusion rates, as compared to CFCs (k = 8.2 W/mK), due to which they escape out of the foam pores and are replaced by air (k = 0.027 W/mK) (Macchi-Tejeda et al., 2007). Researchers at Oak Ridge National Laboratory claimed that the thermal conductivity of cyclo-pentane filled PU foam increases from 0.0215W/mK to 0.027W/mK in first year and to 0.028W/mK gradually (Wilkes et al., 2002).

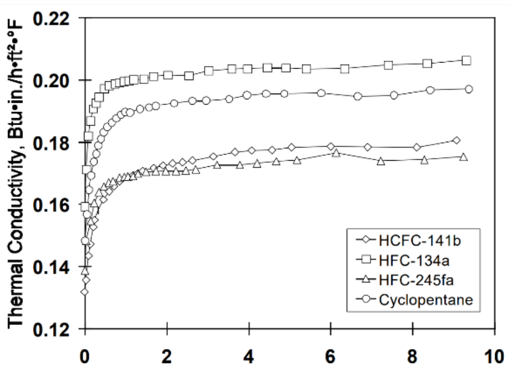

Figure 2: Aged thermal conductivity of PU foam for simulated refrigerator wall. (Wilkes, et al., 2002)

The effect of ageing on the thermal conductivity of Vacuum Insulation Panels is equally significant. It is well known that the overall thermal conductivity follows an S-curve when plotted with pressure on x-axis in log scale (figure 3). The transmission of air and water vapour inside the VIP core through envelope leads to rise in VIP pressure and thus a rise in overall thermal conductivity. The transmission of these components depend on the pressure inside VIP, the quality of the envelope and the area of VIP. In this study, an initial VIP pressure of 0.1 mbar has been considered which rises in step of 1.5 mbars each year for all the VIPs and the variation of thermal conductivity has been taken from Simmler et al. (2005) and Alam et al. (2014).

2.5. Payback period

The per-unit cost of VIPs is more than two times the cost of PU foam. This gives a clear indication that the initial cost of VIP insulated refrigerator will be higher than present PU foam ones. On the other hand, the VIP insulated refrigerators are expected to save on cost of electricity due to lower energy consumption. Based on this information and the data obtained from heat transfer simulations, a payback period was defined as the number of years it requires to break-even the cost if one buys a VIP insulated refrigerator instead of PU foam one. The payback period is identified as the point where the cumulative electricity cost difference line (delta EC) intersects the increased cost line (delta IC).

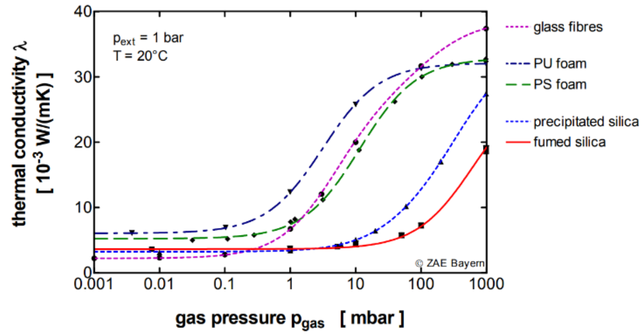

Figure 3: Variation of thermal conductivity of various core materials with pressure (Simmler, et al., 2005)

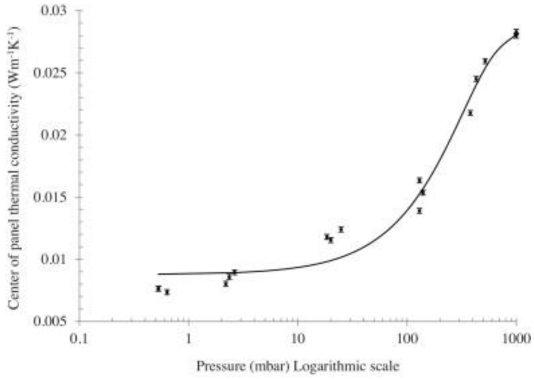

Figure 4: Variation of thermal conductivity of alternative core material with pressure. (Alam, et al., 2014)

3. RESULTS AND DISCUSSIONS

The parametric study for thickness optimisation resulted in set of values plotted as 3D surfaces (figure 5-8). The x and y-coordinate was the fridge and freezer thickness respectively and the z-

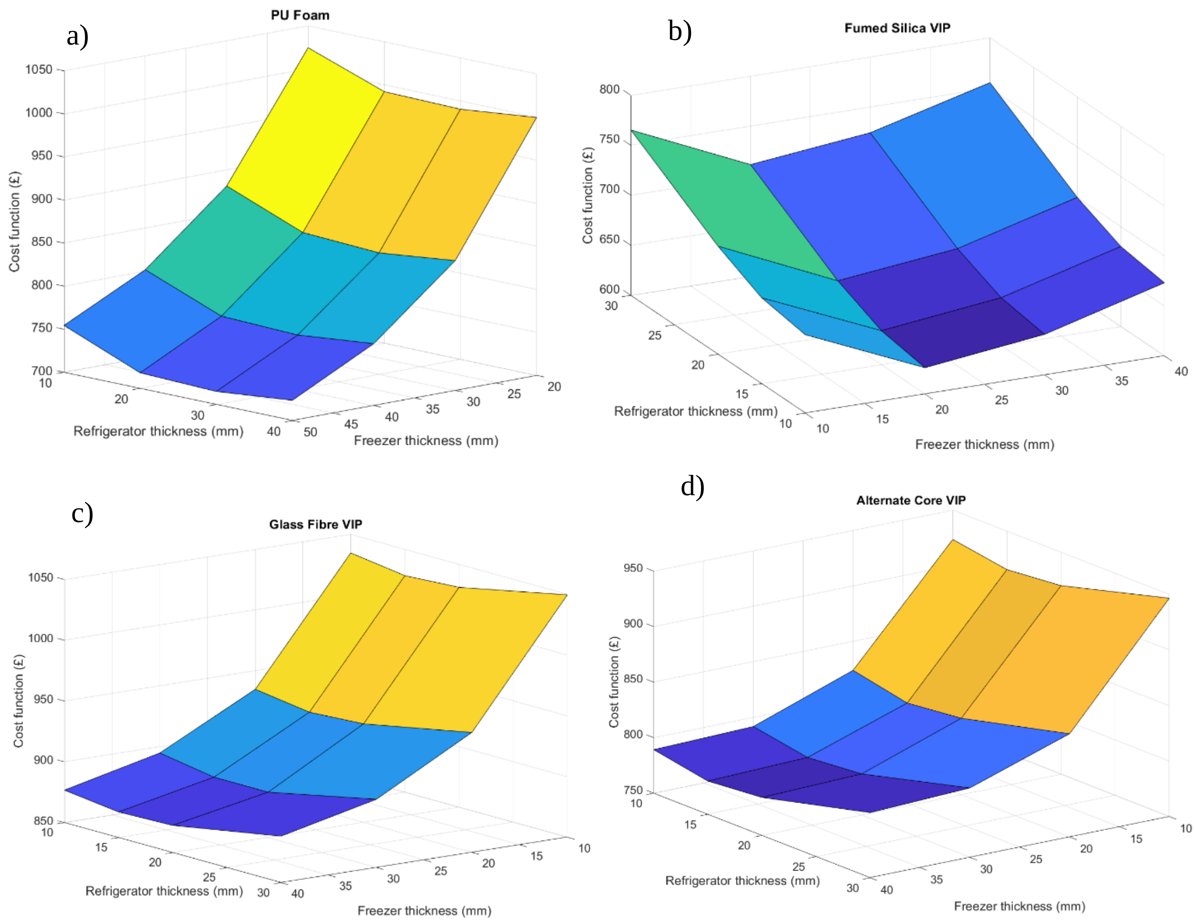

Figure 7: Parametric thickness optimisation surface for a) PU foam b) Fumed silica VIP c) Glass fibre VIP d) Alternate core VIP

coordinate was the cost function (equation 1). The minima on the surface was chosen as the optimum value for fridge and freezer thickness (see table 3). It can be observed that optimum thickness for VIPs is lower than PU foam insulation which is due to low thermal performance and lower cost of PU foam. Also, the optimum thickness of freezer insulation is always higher than the fridge insulation because more heat is transferred to freezer due to large temperature difference between freezer and ambient temperature (around 45°C).

An analysis was then performed on the insulation with optimised thicknesses (Table 3). It was observed that fumed silica VIP offered the minimum energy consumption over lifetime (19.6% lesser than PU foam insulated refrigerator), results in the least value for cost function (£ 626.32) and the highest inner volume (598 litres; 148 litres more than PU foam insulated), because of its lowest optimum thicknesses. A weight gain of 2.48 kg from PU foam refrigerator was observed due to higher density of fumed silica VIP (2.5 times PU foam). Glass fibre, being the densest (250 kg/m^3), resulted a weight increase of 19.56 kg. Also, due to its ageing characteristics, its energy consumption increases, leading to higher value of cost function.

Table 3: Optimised thickness of insulation materials and its relative effects

	Fridge insulation thickness (t_{fridge})	Freezer insulation thickness ($t_{freezer}$)	Lifetime energy consumption {% change} (kWh)	Cost function (£)	CO_2e emissions (kg)	Weight of insulation (kg)	Inner volume (l)
M1	30	50	3802.72 {0}	715.14	1168.2	24.72	450
M2	10	20	3057.62 {19.6}	626.32	939.3	27.2	598
M3	15	40	4418.38 {-16.2}	871.14	1357.3	44.28	527
M4	15	40	3405.41 {10.4}	779.94	1046.1	38.96	527

The transmission load for fridge and freezer at the end of each year of its lifetime is shown in figure 9 and 10. Surprisingly, at the optimised thickness, the energy consumption of fridge is minimum when it is insulated with PU foam, whereas the effect is fully reversed in freezers. This indicates that the marginal rate of return on insulating a freezer with a VIP is more than insulating a fridge.
The effect of ageing can be well observed in all the materials. Out of all materials, glass fibre VIPs are worst hit by ageing. The freezer transmission load for glass fibre VIP loses its VIP characteristics (low transmission load) just after 2 years and even surpasses PU foam in 8 years.

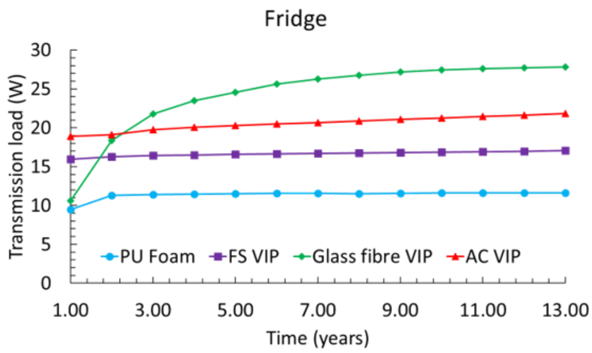

Figure 9: Yearly transmission load from a fridge

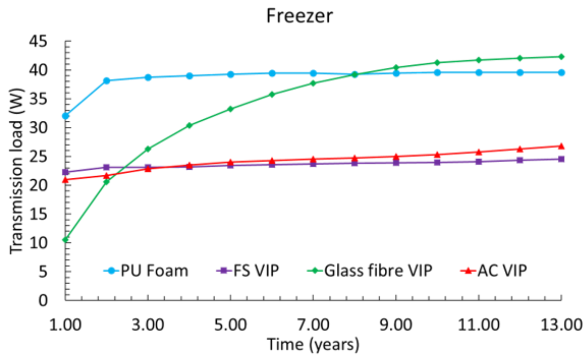

Figure 10: Yearly transmission load from a freezer

The payback period was calculated as the abscissa of the intersection point of increase in insulation material cost (delta IC) with respect to PU foam insulation and the cumulative gain because of reduced electricity bills (delta EC). The fumed silica VIP broke even in 3 years, because of excellent thermal and ageing properties of fumed silica (figure 11). A significantly higher payback period of 8-9 years is reported in literature (Hammond & Evans, 2014), the discrepancy being the underlying assumptions. In this study, the authors believe that VIPs of any size and shape could be manufactured in near future, which lowers the heat leakage from areas without VIPs. Also, the consideration of effect of ageing of foam plays its role in terms of increased energy cost over the life time of refrigerator and decreased payback.
The VIP with glass fibre core performed very well in the first year but its performance deteriorated as it aged (figure 12). This is because the thermal conductivity of glass fibre is very low initially (0.002 W/mK) but rises rapidly as the pressure inside the VIP increases and eventually becomes higher

than that of PU foam. The alternate core VIP doesn't break even either, even after reduced initial cost (figure 13). The reduced cost is achieved by addition of components which increase the overall thermal conductivity of VIP cores. This leads to two outcomes: i) usage of higher thickness of VIPs for insulation which leads to increased initial cost and ii) higher overall aged thermal conductivity.

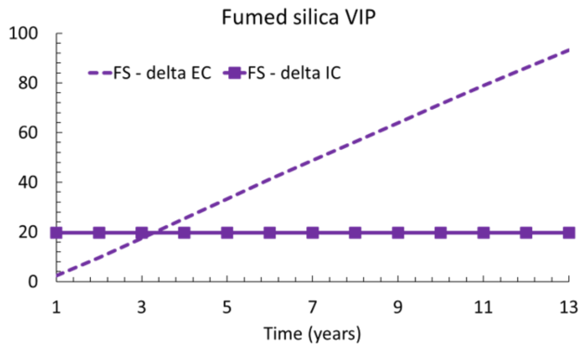

Figure 11: Payback period calculation for fumed silica VIP

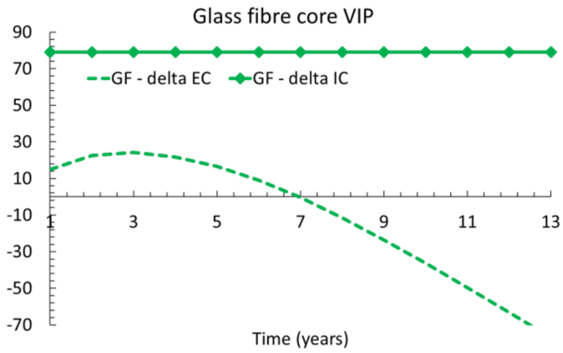

Figure 12: Payback period calculation for glass fibre VIP

CONCLUSIONS AND FUTURE WORKS

Four different insulation materials were compared for their thermal, physical and economic performance by computer modelling, starting with identification of their optimum thicknesses independently for fridge and freezer to reduce the initial and operational costs through a parametric study. The results were analysed to compare three different VIP and PU foam on the basis of their transmission gain, carbon footprint over the lifetime and the payback period. Results indicated that a fridge insulated with 10mm thick and the freezer with 20mm thick fumed silica VIP reduced the energy consumption by 19.6% while increasing the inner volume by 148 litres and weight by 2.48 kg when compared with PU foam insulated refrigerator.

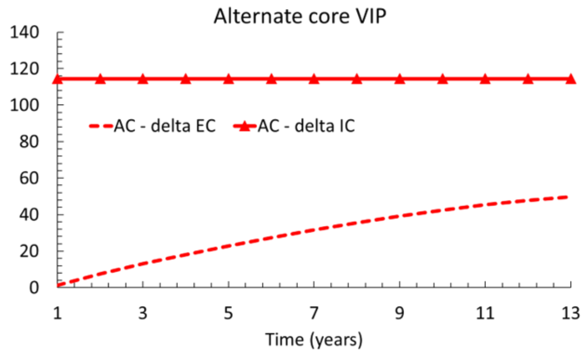

Figure 13: Payback period calculation for alternate core VIP

This study serves as a motivation for VIP manufacturers to make VIPs in various shapes and sizes to be fitted in refrigerators. Research is needed into new alternative materials for cores which could lower the VIP cost by 50%; into heat transfer phenomena through VIPs and the various material properties affecting it and into low permeating and low conducting envelopes so that glass fibre cores can be fully exploited. Both, policy makers and industry should promote research in this field.

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