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Journal of Non-Crystalline Solids xxx (2004) xxx–xxx
JOURNAL OF
NON-CRYSTALLINE SOLIDS
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Development of windows based on highly insulating aerogel glazings

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Abstract

Within a finished and a current EU project, research and development are being carried out on the use of monolithic silica aerogel as transparent insulation in windows. Results related to the window application will be presented here. At the thermal envelope of buildings, the window area is the weakest part with respect to heat loss, but at the same time, this area also provides advantages, e.g., solar energy gain. Glazing prototypes have been made of aerogel tiles of about $55 \times 55\,\mathrm{cm}^2$ (fabricated within the EU projects). The tiles are evacuated rapidly and easily sealed between two glass panes and a specific rim seal. A heat-treatment phase (after the supercritical CO_2 drying) of the aerogel is currently being developed in order to improve its optical quality. This step increases the solar transmittance by ~6 percentage points. For glazing prototypes with an aerogel thickness of ~15 mm, a center heat-loss coefficient of $<0.7\,\mathrm{W m^{-2} K^{-1}}$ and a solar transmittance of 76% have been obtained.

IDT: A120; S160; T140
PACS: 81.05.Zx; 89.30.+f; 89.20.+a

1. Introduction

Monolithic silica aerogel (aerogel) is a highly porous material with pore diameters in the range of 10–100 nm [1]. The porosity is >90%, which combined with the nanometer pore size makes aerogel a highly insulating material with a thermal conductivity lower than that of still air [2]. A further decrease in thermal conductivity can be achieved if the aerogel is evacuated below ~50 hPa, where thermal conductivity in the pore gas is essentially eliminated [3].

In addition to the low thermal conductivity of silica aerogels, a high solar energy and daylight transmittance is achieved, which makes these very interesting materials for use in highly energy-efficient windows [4]. The compression strength of aerogel is sufficient to withstand atmospheric pressure if evacuated, but the tensile strength is very low, which makes the material fragile, i.e., if in contact with water, the surface tension in the pores would demolish the aerogel structure. So, the application of aerogel for window glazing requires the aerogel to be protected against water and tensile stress. Placing the aerogel between two layers of glass and applying a gas- and moisture-tight rim seal can isolate the aerogel from such stresses. When the assembly is evacuated to a rough vacuum, only compression stresses are present in the aerogel due to the external atmospheric pressure.

Fig. 1 shows the advantage of aerogel windows relative to commercially available low-energy glazing for which the reduction in the coefficient of heat loss (U-value) is achieved by multiple layers of glass and low emissive coatings – measures that also reduce the solar energy and daylight transmittance. In contrast, aerogel glazing has a solar energy transmittance equal to plain double glazing and at the same time a heat loss coefficient equal to the best triple-layered gas-filled glazing units. Monolithic silica aerogel is the only known material that has this excellent combination of high solar-

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doi:10.1016/j.jnoncrysol.2004.06.047

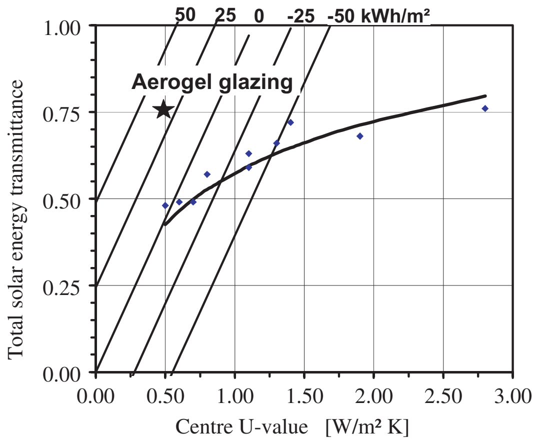

Fig. 1. Thermal and solar properties of HILIT/HILIT+ aerogel glazing (15 mm aerogel) compared with typical commercially available low-energy glazings. The dots mark the values for specific glazing units. The solid curved line shows the trends in traditional glazing development. The straight lines show the net energy balance during the heating season for a north-facing glazing in a Danish climate.

and light transmittance and low thermal conductivity – materials parameters that make it possible to achieve a net energy gain during the heating season for north-facing windows in a northern European climate such as the Danish climate (Fig. 1).

Utilizing the passive solar energy that passes through windows is an important factor in reducing the annual energy consumption for space-heating in northern European countries and has been the background for the research and development projects HILIT [5] and HILIT+ [6], financed in part by the European Commission. The objectives of both projects were to improve the aerogel fabrication process with respect to materials properties (both thermal and optical) and process parameters (drying duration and safety) and to develop final aerogel glazing prototypes with a total *U*-value $<0.6\,\mathrm{W m^{-2} K^{-1}}$ and a total solar energy transmittance >75%.

The aerogel fabrication process, which has been previously described [7,8], is based on a previously patented synthesis route performed with commercialized silica precursors (PCAS) [1] [9]. The present paper concentrates on the research and development of silica aerogel glazing and its application.

2. Overall coefficient of heat loss

The ideal rim seal should be 100% gas- and moisture tight and at the same time have a thermal conductivity equal to that of evacuated aerogel in order to avoid thermal bridge effects along the glazing perimeter. Such a solution does not exist and the main R&D task has been to develop a solution as close to ideal as possible. Fig. 2 shows the effect on the total aerogel glazing *U*-value for different commercial available rim seal solutions known from the glazing industry.

Several ways exist to minimize the thermal bridge effect: (1) select materials with a low thermal conductivity; (2) minimize the material thickness; (3) increase the heat flow path-length; or (4) a combination of all three [4]. The rim seal solutions shown in Fig. 2 are used in sealed glazing units and should act as gas- and moisture barriers as well as a structural element to maintain the desired glass distance, *D*, see Fig. 2.

In aerogel glazing, the glass distance is determined by the aerogel layer, which has sufficient strength to maintain the glass distance even when evacuated. Therefore rim seal solutions for aerogel glazing do not need to provide any structural strength, which makes foil solutions possible. Metal foils with a thickness >0.1 mm and glass are the only materials that are 100% tight against gas- and moisture diffusion. Metal foils with a thickness <0.1 mm are not airtight because of pinholes. Different laminated plastic foil solutions developed for vacuum insulation panels have a very low permeability that may be sufficient if a limited lifetime of the glazing is allowed.

Glass is considered too fragile, leaving metal and laminated plastic foils as the most suitable rim seals. The thermal bridge effect has been calculated for different metal foils and for a laminated plastic foil developed for vacuum insulation – Mylar® 250 RSBL300 from

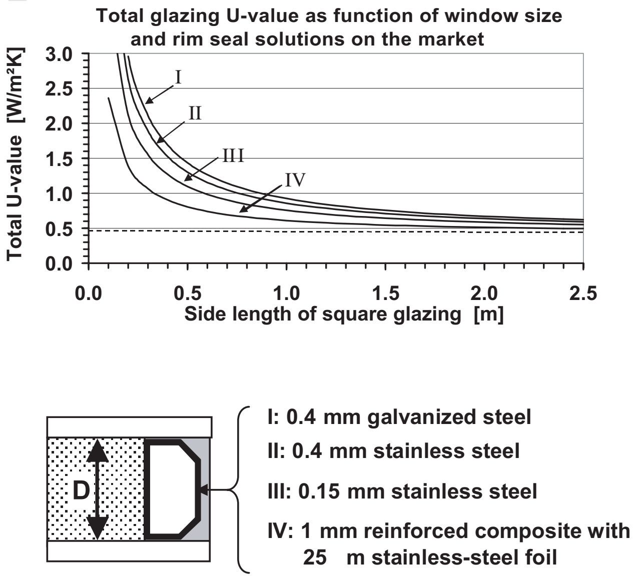

Fig. 2. The calculated overall coefficient of heat loss (*U*-value) as a function of glazing size and commercially available rim seal solutions for a square aerogel glazing with ∼20 mm aerogel thickness and a center *U*-value of $0.41\,\mathrm{W m^{-2} K^{-1}}$. I: 0.2 mm stainless steel; II: 0.1 mm stainless steel; III: 0.05 mm stainless steel; IV: Mylar® 250 RSBL300 [10].

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[1] http://www.pcas.fr

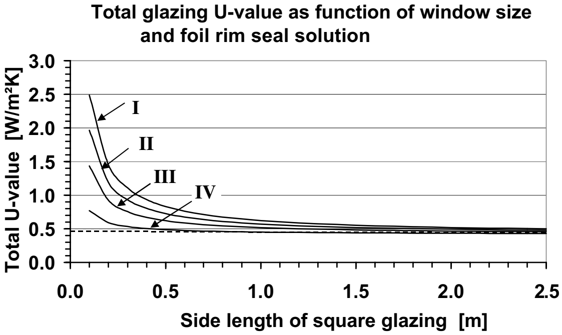


Fig. 3. Calculated overall coefficient of heat loss (*U*-value) as a function of glazing size and foil rim seal solutions for a square aerogel glazing with a center *U*-value of 0.41 $\mathrm{W m^{-2} K^{-1}}$ (~20 mm aerogel thickness). I: 0.2 mm stainless steel; II: 0.1 mm stainless steel; III: 0.05 mm stainless steel; IV: Mylar® 250 RSBL300 [10].

DuPont [10]. The foil is made of several different plastic layers and a 13 nm thick aluminium layer. The total foil thickness is <0.1 mm. The thermal advantage of laminated plastic foil relative to stainless-steel foils is shown in Fig. 3. The barrier properties of the Mylar® foil are sufficient, according to specifications given by the manufacturer (ASTM tests F1249 and D3985), to keep the required vacuum for at least 30 years if the foil is protected against water and UV-radiation.

3. Solar energy transmittance

The advantage of aerogel glazing compared to other highly insulating glazing units is its high solar energy transmittance, which in cold climates has a large influence on the annual energy consumption for space heating. For a new single family house in a Danish climate, the annual energy savings amounts to about 2300 kWh per year (~16%) if conventional argon-filled triple glazing (*U*-value = 0.5 $\mathrm{W m^{-2} K^{-1}}$, total solar energy transmittance = 0.4) is replaced with aerogel glazing (*U*-value = 0.5 $\mathrm{W m^{-2} K^{-1}}$, total solar energy transmittance = 0.75). For a low-energy house the savings fall to 1600 kWh per year, but this amount still corresponds to 25% of the annual heating demand. The energetic benefit of aerogel glazing decreases in warmer climates and may cause severe over-heating problems even during the heating season. A high solar transmittance may result in high indoor temperatures during summertime even in colder climates and solar shading and enhanced venting may be needed.

The basic aerogel made as part of the European projects has a solar energy transmittance of ~70% for an aerogel thickness of 15 mm. A subsequent heat treatment of the aerogel to a temperature of 425 °C improves the optical quality, yielding a considerable increase in the solar energy transmittance (~6%).

Table 1
Estimated solar-energy transmittance for aerogel glazing and commercial low-energy glazing with and without anti-reflective treated, low-iron-content glass. Both glazings have a heat loss coefficient of ~0.6 $\mathrm{W m^{-2} K^{-1}}$ and all glass panes have a thickness of 4 mm glass; the aerogel thickness is 15 mm

Glazing	Common float glass (%)	Anti reflective treated low-iron-content glass (%)
Triple-glazed unit	45	59
Aerogel glazing	63	76

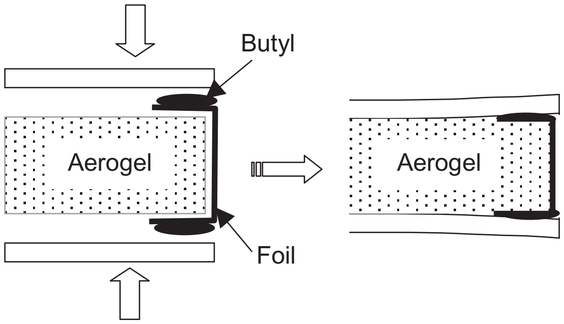
Placing the aerogel between two layers of glass reduces the solar energy transmittance because of absorption and reflection in the glass panes. The absorption depends primarily on the iron content in the glass and the glass thickness. A common 4 mm thick float glass absorbs ~10% of the solar energy, while a 3 mm thick glass absorbs ~8%. The iron content in the glass furthermore changes the color of the transmitted daylight. Float glass with a very low iron content reduces the solar energy absorption to <1% almost independently of glass thickness.

The reflection losses occur when solar radiation hits the glass surface and amount to a loss of ~8% for a single layer of glass. This value can be changed by surface treatment of the glass panes. A commercial durable treatment has been developed by SUNARC [11] (mainly applied for solar collector covers) and reduces the loss due to reflection to ~3%. Table 1 shows the estimated benefit of using anti-reflective-treated, low-iron content glass for aerogel glazing and common low-energy glazing units. An improvement of the solar energy transmittance of ~13%-point is found for both types of glazing, but even if triple glazing is fully optimized, the solar energy transmittance is still lower than for non-optimized aerogel glazing.

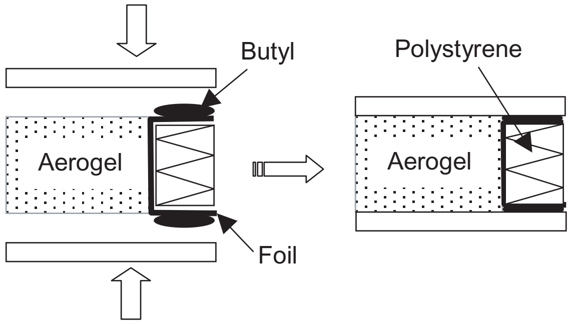
4. Evacuation and air tightness

Evacuation of the glazing can be performed either during assembly in a vacuum chamber or afterwards through stubs in the glass or rim seal. The diffusion coefficient of air in monolithic silica aerogel is in the range of 10^{-5} to 10^{-6} $\mathrm{m^2 s^{-1}}$ [12,13] making it the governing parameter with respect to evacuation time. Evacuation should therefore take place from one surface of the aerogel in which case only the aerogel thickness determines the evacuation time and not the actual glazing size.

On the basis of the thermal analyses, the use of laminated plastic foils developed for vacuum insulation purposes seems to be the most suitable solution for the rim seal in aerogel glazing. The big challenge is making an airtight connection between the foil and the glass panes. From a thermal point of view, the total rim-seal thick-



(a) Foil wrapped around aerogel edge



(b) Foil wrapped around polystyrene spacer

Fig. 4. Two different approaches for application of the foil rim seal solution.

ness should be as thin as possible, which can be obtained by the option shown in Fig. 4(a), where the foil is wrapped around the aerogel edges. A butyl sealant is applied between the glass panes and the foil before evacuation of the aerogel glazing. During evacuation, the atmospheric pressure presses the glass panes against the aerogel and the butyl sealant to make a firm and airtight joint between the foil and the glass panes. The principle is that of 'self tightening' and was developed in a previous European project [14].

The drawback is that the glazing will not be flat due to the additional thickness along the glazing perimeter, which poses an aesthetics problem. The bending of the glass panes furthermore results in tensile stresses at the glass edges and tempered glass is required to avoid breakage. These concerns make the aerogel glazing considerably more expensive. Also the process of wrapping the foil around the aerogel edges is difficult due to the fragility of the aerogel.

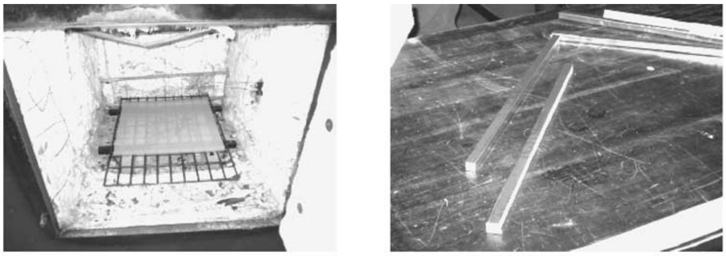
In the HILIT project [5], the drawbacks have been overcome by folding the foil around rods of polystyrene as shown in Fig. 4(b). The height of the polystyrene is a few millimeters less than the aerogel thickness making room for the butyl sealant. The polystyrene spacer provides support for the foil and has a compression strength great enough to ensure the necessary compression of the butyl sealant when the aerogel glazing is evacuated. A flat glazing is achieved by proper choice of the polystyrene dimension. Furthermore handling the foil and application of the butyl sealants can be done without touching the aerogel edges. The disadvantages of this solution are an increased thermal bridge effect of the rim seal and a more difficult corner solution with enhanced risk of leakages.

5. Prototypes

The investigations and developments described in the previous sections have been implemented in the laboratory in a process to produce prototypes of aerogel glazing. The prototypes were primarily made for testing of thermal and optical properties and for testing the assembly process in a pre-industrial scale. The core element is the Aerogel Glazing Evacuation Apparatus (AGEA) developed in a national Danish project [15]. The AGEA is a vacuum chamber that makes it possible to evacuate and assemble the aerogel glazing in few minutes as the evacuation takes place from the top aerogel surface and the edges.

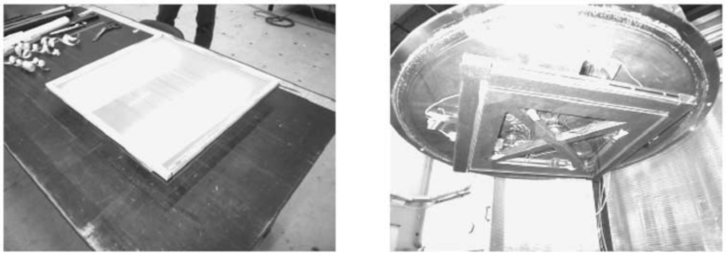
The rim seal is made by the method shown in Fig. 4(b) with polystyrene rods wrapped in Mylar® 250 RSBL300 foil [10]. Fig. 5 shows the total process from application of the foil on the polystyrene rods to the final, ready-to-use glazing. The process is as follows:

- The heat-treated aerogel ($T = 425\,°\mathrm{C}$) is placed on the lower glass pane.
- A butyl sealant strip is applied to one side of the polystyrene rods with foil; the rods are then placed along the aerogel edges with the sealant facing the lower glass and pressed slightly into position.
- The corners are joined with butyl sealant and a butyl sealant strip is applied on top of the polystyrene rods.
- The top glass pane is centered in the vacuum chamber and a small self-adhesive metal disk is placed on the top glass pane opposite to electromagnets in the vacuum chamber lid. The lid is closed and the magnets are activated, which affixes the upper glass to the lid in the correct position.
- The vacuum chamber lid is opened and the lower glazing with aerogel and rim solution is placed in the vacuum chamber.
- The vacuum chamber lid is closed and the evacuation started. The evacuation is continued until a pressure of ~1 hPa has been maintained for 5 min. Total evacuation time is ~30 min.
- The upper glass pane is lowered and pressed firmly against the aerogel and rim seal solution to make an airtight connection between glass panes and rim seal.



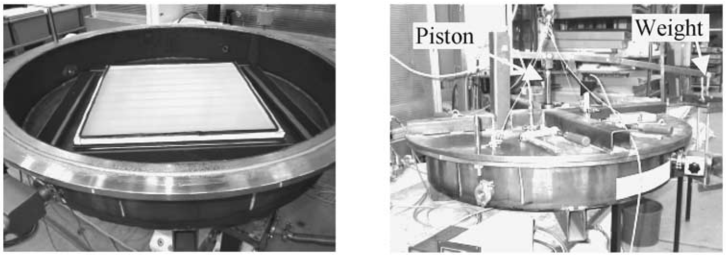
(a) Heat treatment at 425 °C

(b) Rim seal of foil and polystyrene spacer.



(c) Lower glass + aerogel + rim seal

(d) Upper glass fixed to lid of vacuum chamber by means of electromagnets



(e) Lower glass + aerogel + rim seal in vacuum chamber

(f) Vacuum chamber closed and upper glass pressed against rim seal and aerogel by means of the piston

(g) Aerogel glazing in the chamber after evacuation

(h) Final aerogel glazing

Fig. 5. The total aerogel prototype glazing production process.

- The chamber is gently vented and atmospheric pressure further compresses the glazing securing the complete compression of the butyl sealing between the foil and the glass panes.

6. Results

Several prototypes have been made during the HILIT project [5] based on aerogel sheets made by Airglass AB following the optimized aerogel fabrication process developed during the project on the basis of the previously patented route [7]. The aerogel thickness was $15 \pm 1\,\mathrm{mm}$.

The center *U*-values of the optimized glazing prototypes have been measured by means of a hot-plate apparatus. The average center *U*-value is found to be $0.66 \pm 0.03\,\mathrm{W m^{-2} K^{-1}}$, which with the average aerogel thickness of 14.8 mm corresponds to an estimated thermal conductivity of $0.010\,\mathrm{W m^{-2} K^{-1}}$. This indirectly determined thermal conductivity agrees with the measured materials properties at a pressure level of 1–10 hPa.

Four of the optimized prototypes have been used for a test window (Fig. 6) measuring $1.2 \times 1.2\,\mathrm{m^2}$ designed for hotbox measurements of the overall *U*-value. The well-insulated framing system is made only to fix in

Fig. 6. Four optimized aerogel prototypes joined in a test frame for hotbox measurements.

place the four glazings and will not withstand exposure to real climate for longer periods. The measured overall *U*-value of the glazing is deduced from the measurements by subtracting the heat loss through the framing system. The average total *U*-value is $0.72 \pm 0.04\,\mathrm{W m^{-2} K^{-1}}$, which when compared to the average center value of $0.66\,\mathrm{W m^{-2} K^{-1}}$ confirms the very small thermal bridge effect of the developed rim seal solution. The average direct solar energy transmittance for the four glazings was measured to 73 ± 2%. The total solar energy transmittance, the g-value, has not been measured but would be a few percentage points higher.

The optical quality of aerogel glazing is not at the same level as conventional glazing units, especially when exposed to non-perpendicular direct radiation where some diffusion of the radiation in the aerogel occurs and makes the glazing appear hazy. But the optical quality has been improved considerably thanks to the research carried out as part of the European projects [5,6,14] to a level where almost no disturbance in the view-through is present if the aerogel glazing is shielded against direct radiation (Figs. 5 and 6). This adjustment makes aerogel glazing an excellent option for improved daylight utilization combined with a reasonable prospect of placing large areas of aerogel glazing in north facades. Because of the very good insularity and high solar- and daylight transmittance of aerogel glazing, this home improvement can be done without energy loss or even with energy gain (Fig. 1). Such a combination of improvements cannot be obtained with any other known glazing or daylight component options.

Despite the promising results already achieved, research is still focused on further improvement of the optical quality through detailed studies of the sol-gel process and a post-heat treatment aiming at an optical quality comparable to ordinary glass.

7. Conclusions

Within the present European projects HILIT/HILIT+, transparent and insulating plane monolithic silica aerogel tiles are fabricated at a large-scale on the basis of a previously patented synthesis route. Evacuated aerogel glazings of $\sim 55 \times 55\,\mathrm{cm^2}$ have been made – the size dictated by the production plant dimensions at Airglass AB.

A rim seal has been developed with the required barrier properties against atmospheric air and water vapor to achieve a limited thermal bridge effect and ensure a theoretical lifetime of the glazing of about 30 years. The dimensions of the rim seal are chosen so that a completely flat glazing is obtained, making it possible to use non-tempered glass. The final assembling and evacuation takes place in a vacuum chamber. The evacuation time is ~30 min resulting in a final pressure in the aerogel of 5 hPa.

The solar- and daylight transmittance of the aerogel glazing is optimized by means of low-iron glass covers with an anti reflection coating. The optical quality has reached a level with minimal disturbance in the view-through except if exposed to direct non-perpendicular radiation where diffusion of the light becomes significant. The measured center *U*-value is $0.66\,\mathrm{W m^{-2} K^{-1}}$. Upon including the thermal losses in the rim seal, an overall *U*-value for the $55 \times 55\,\mathrm{cm^2}$ glazing is found to $0.72\,\mathrm{W m^{-2} K^{-1}}$ as deduced from the hotbox measurements on a window with 4 aerogel glazings joined in an interim frame.

The direct solar transmittance is measured at laboratory conditions as >75%, making the aerogel glazings developed in this project superior to other highly insulating glazings on the market with respect to energetic performance in northern European or equivalent climates. The total solar energy transmittance, the g-value, has not been measured but will be 1–2 percentage-points higher than the direct solar transmittance. Within the framework of the present HILIT+ project, current studies seek to further optimize the aerogel fabrication process by decreasing the duration of supercritical drying of the aerogel panes.

Acknowledgments

The research is funded in part by the European Commission within the frameworks of the Non-Nuclear Energy Programme – JOULE III and the Energy, Environment and Sustainable Development Programme – EESD; the contracts JOR3-CT97-0187 (acronym: HILIT) and ENK6-CT-2002-00648 (acronym: HILIT+). The authors would like to thank the participants in the two projects on which this work is based: M. Rydén (Air Liquide Gas AB, Sweden), L. Gullberg and G. Petermann (Airglass AB, Sweden), B. Chevalier (CSTB, France), P. Achard, A. Rigacci, and Y. Masmoudi (École des Mines de Paris, France), P. Nitz and W. Platzer (Fraunhofer ISE, Germany), B. Sunden (LTH, Sweden), M.-A. Einarsrud, E. Nilsen, and R.A. Strøm (NTNU, Norway), M. Durant and D. Valette (PCAS, France), H. Brauer (Saint-Gobain Glass Nordic), S. Bauthier and G.M. Pajonk (Université Claude Bernard Lyon 1, France). The AGEA has been developed and built with support from the Danish Energy Agency.

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