Advanced Buildings Skins: Experimental Evaluation of a Prototypical Translucent Thermal Storage Element

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INTRODUCTION

The ideal building skin in a heating dominated region should be well insulated, utilize maximum solar energy to reduce the heating load and offset the daytime use of energy required for lighting. Critical envelope functions are storage of thermal energy gained from solar energy, thermal insulation to the exterior and control of solar gain. Due to variable external environmental conditions it is also desirable to create an envelope that is able to respond actively to these changes and adjust its properties to minimize energy consumption. With materials available today and new materials to be potentially available for construction in the near future, such a building envelope can be designed as a skin of multiple functional layers.

The presented study is part of a larger project exploring the use of advanced materials in building skins to create such functional building envelopes. The presentation focuses on the experimental evaluation of the performance of a prototypical façade panel with respect to its ability to effectively mediate external environmental conditions. Construction issues, design considerations, and a quantitative analysis of the implications for residential heating and cooling energy requirements are discussed in "Advanced Building Skins: translucent thermal storage elements" [Kienzl, 1999].

BACKGROUND

The proposed panel incorporates past research findings for environmentally responsive building envelope design with special consideration of new material developments. In addition to the above-mentioned functions, the proposed component was designed as a translucent element to reduce artificial lighting loads and to expose the visual characteristics of the materials.

The function of each layer determined the sequence of layers within the panel: the most exterior layer to control of solar gain to prevent overheating; the middle layer to provide thermal insulation to prevent heat loss from the inside; and the innermost layer (exposed to the interior) to provide thermal storage as [see Fig. 1]. One material for each layer was identified: electro-chromic glass for control of solar gain, granular Aerogel as thermal insulator and calcium chloride hexahydrate as a phase change material (PCM) for thermal storage. Selection of the materials was based on an in-depth study of new glazing and insulation technologies for low energy building envelope construction [see Kienzl, Advanced Building Skins, 1999]. The superior performance of each of the selected materials for their respective purpose and the desire to investigate the potential of these advanced materials in their combination was the primary rational for these selections.

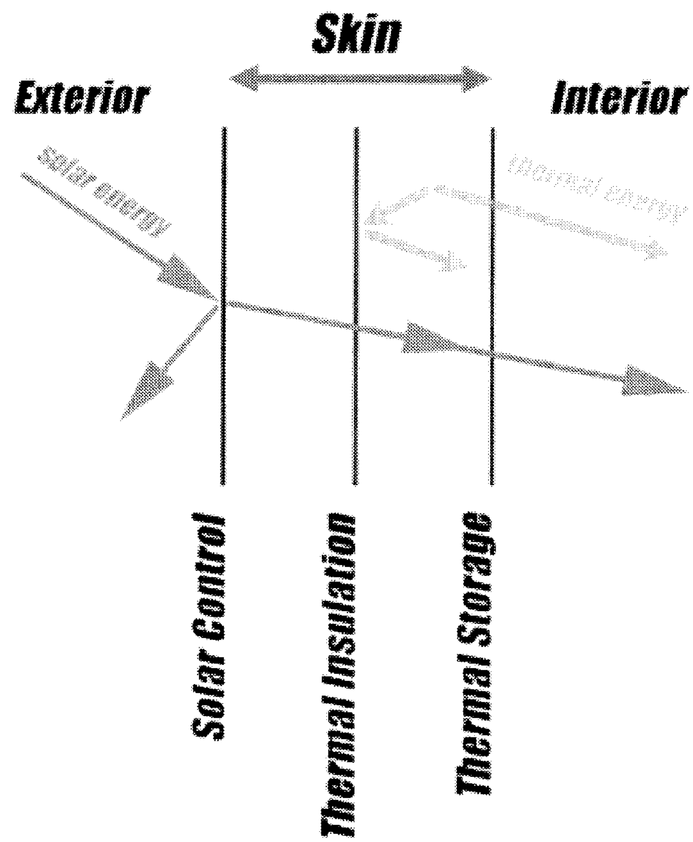

Fig. 1. Sequence of layers in prototype assembly.

The assembly follows the principles of a thermal storage wall with translucent insulation as explored in recent years among others by the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany [see Marko, et.al., Thermische Solarenergienutzung an Gebäuden, 1996]. Studies with phase change material and translucent insulation at the Federal Institute for Materials Testing in Zurich, Switzerland, have highlighted the potential for the use of PCM in a similar thermal storage wall configuration [see Manz, Sonnenstrahlungsbeladene Latentwärmespeicher in Gebäudefassaden, 1996]. Electro-chromic glass was introduced for this study to add the advantages of active control of solar gain and is based on recent work at the Lawrence Berkeley National Laboratory.

DESCRIPTION OF ASSEMBLY

The proposed assembly combined all three of these materials into one façade panel. Framing technologies similar to conventional glazing assemblies have been used in earlier studies for Aerogel windows [see Dawson, Light Spirited, 1997] and proved suitable for such applications. In the commercial production of electro-chromic windows, electro-chromic panes are assembled with a second glass pane into double pane units. This framing technology follows well-established industry standards. The proposed panel uses this earlier work as a starting point for the detailing of the panel. Three layers of glass, two panes of float glass and one electro-chromic glass pane, spaced with aluminum edges and sealed with silicon were chosen for the design of the container for granular Aerogel and PCM.

Based on earlier studies with Aerogel and this particular type of phase change material [see Beck, Optical Investigation of Granular Aerogel Fills, 1994], as well as the available framing materials, glass panes were spaced 20mm (0.75 inches) apart. This created two cavities, which were filled with Aerogel and PCM [see Fig. 2].

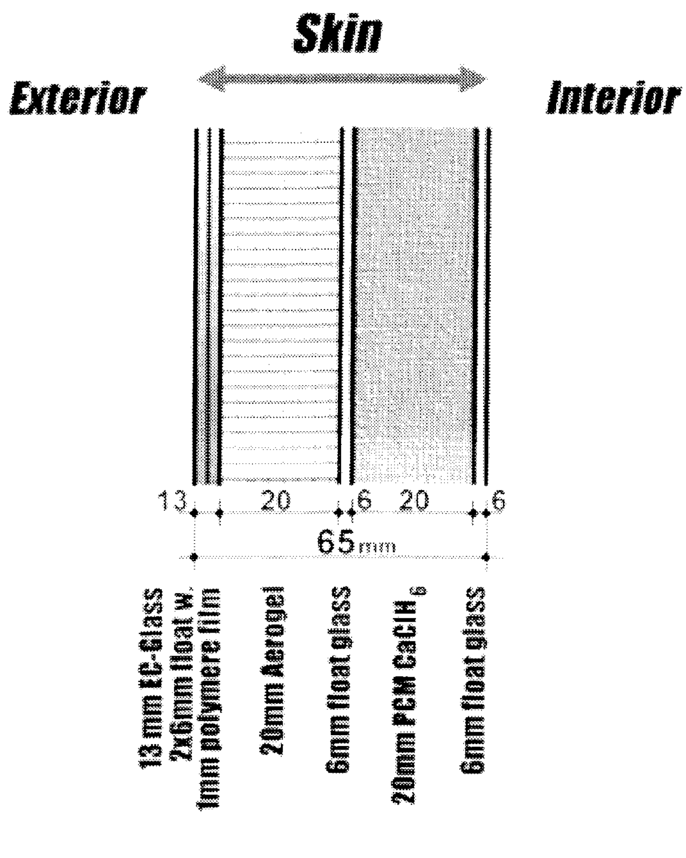

Fig. 2. Construction of proposed component.

Through publications and contacts with industry, data on all of these materials was obtained. This information served as a basis of the investigation and included thermal conductivity, specific heat, fusion enthalpy for the PCM, density and optical properties, where available. Data that was not available for the materials has been approximated from standard publications or other scientific records.

For the creation of mock-ups and the final prototype, material samples were collected from manufacturers and were utilized to manufacturers guidelines. Aerogel was supplied as granulate with diameters ranging from 0.5 to 3mm. The phase change material was a mix of untreated water and commercially available calcium chloride pellets and set to a temperature of fusion at 26 deg. C. Unfortunately, the shipment of electro-chromic glass was overshadowed by problems in the transport and operation of the samples. Therefore electro-chromic glass could not be included in the final experimental configuration. In lieu of this, available numerical data for the properties of electro-chromic glass was used to predict the impact of such glass on the assembly.

The availability of this specific set of materials and their special applicability to the study was a major criteria for the final material selection used in the evaluation. Variations possible with other material properties based on different products were considered. The available materials and data proved sufficient for the purpose and scope of this study.

EXPERIMENTAL CONFIGURATION

The purpose of the experimental part of this study was to evaluate the ability of the prototype to dampen diurnal temperature swings as is typical for thermal mass systems. The use of a thin layer of phase change material activated by solar energy gains transmitted through a translucent insulation material however was a significant variation of the established systems. Therefore, it was critical to explore the impact of the component on a larger system or space in relation to changing environmental conditions.

The strategy chosen for this evaluation was the experimental measurement of a prototype component. For this purpose an environmental test chamber was created to collect data for evaluation.

Description of Test Chamber

The outer design of this chamber consisted of an insulated (R19) enclosure in 2"x6" framing construction. Two highly insulated (R30) control volumes (each 2ft wide, 3ft long and 4ft high) were placed inside this shell. The outer enclosure served as a buffer to minimize the environmental impact on the control volumes from the north, east and west. This configuration was chosen to enable the comparative measurements of two different samples at a later point under similar conditions. The control volumes were attached to the south wall so that they aligned with 2ft by 4ft openings in which façade components were to be installed. The control volumes were surrounded on all five sides exposed to the buffer with rigid insulation and the back walls were removable to access sensors within the control volumes [see Fig. 3, 4]

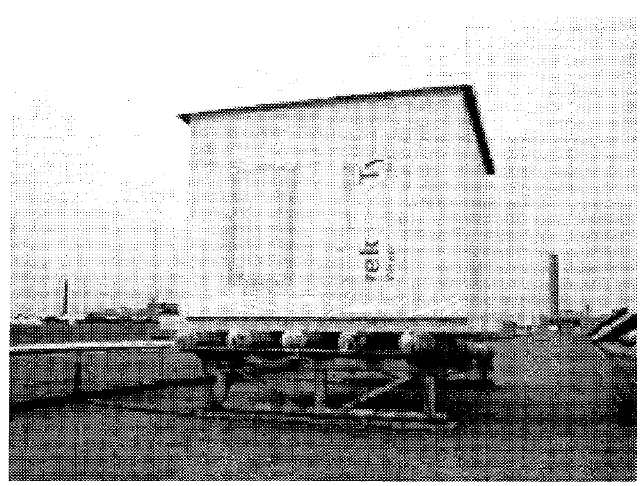

Fig. 3. Test chamber exterior view.

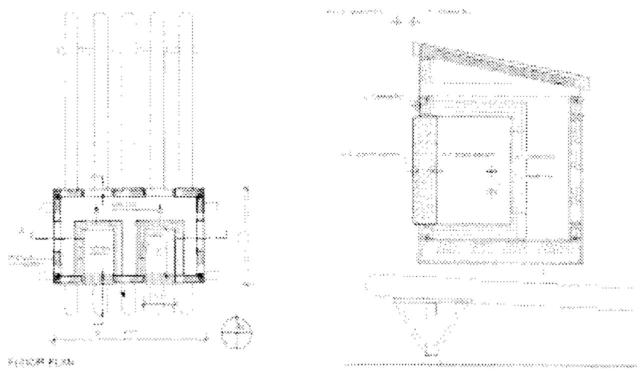

Fig. 4. Test chamber section and floor plan.

Strategy for Data Collection

Measurement devices of the Vital Signs toolkit, developed by University of California at Berkeley, were utilized for the instrumentation of this chamber. HOBO's, small environmental sensors that are able to measure and store data on temperature, light intensity and relative humidity, were placed in the chamber and on the exterior. Five measurement series of six consecutive days were taken during March, April and May of 1999. The first measurement was taken with no element installed and the opening in the south wall was covered with a construction similar to the normal enclosure of the chamber (plywood/ framing/ fiberglass bat insulation). The second and third measurements were taken with an Aerogel window installed to assess the impact of this layer in isolation. The fourth and fifth measurements were taken with PCM elements installed in combination with the Aerogel window, to explore the combined performance [see Fig. 5].

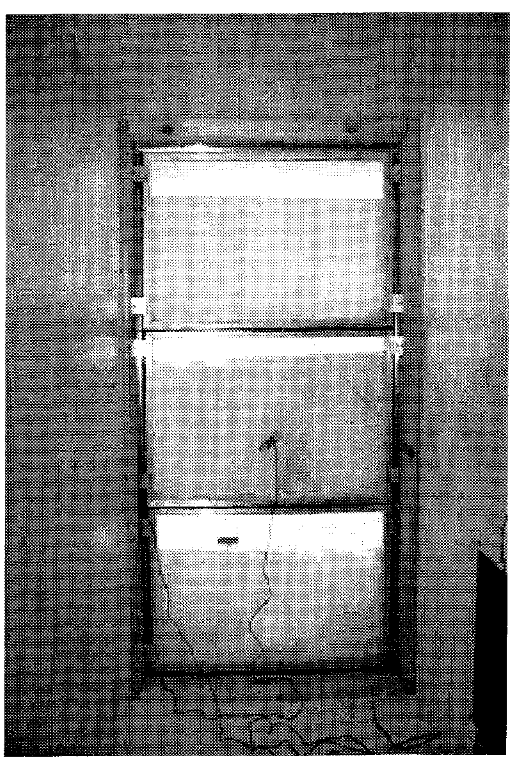

Fig. 5. Interior view of control volume with installed Aerogel and PCM elements.

The relationship of inside to outside temperature was a main focus of these measurements. Through this relationship the effect of the components on the interior situation were observed. In addition, data on surface temperatures, light intensity and relative humidity was collected.

The measurements taken did not allow for an accurate calculation of energy gain and loss as is possible with other experimental configurations. To determine the energy balance, a fixed temperature would have to be maintained in the interior space with heating and cooling equipment. The energy consumed by such equipment to maintain a constant internal temperature could then be used to assess the overall energy exchange between the interior and the exterior. However for the purpose of this initial assessment, it was appropriate to allow the interior temperature to float and to derive qualitative results from observations of the occurring temperature changes.

DISCUSSION OF COLLECTED DATA

In the initial measurement without any element, the interior temperature closely followed the exterior temperature swings. The temperature in the control volume never exceeded high outside temperatures or dropped below lower outside temperatures. Its maximum and minimum temperature values were about 5 deg. C lower, and higher respectively than the exterior [see Fig. 6]. A small time lag of around three hours for the temperature swings on the interior has been observed. This performance can be explained by the mediating effect of the high amount of insulation around the control volume. The temperature in the buffer followed the exterior temperature changes more closely, due to higher infiltration and lower insulation of this zone.

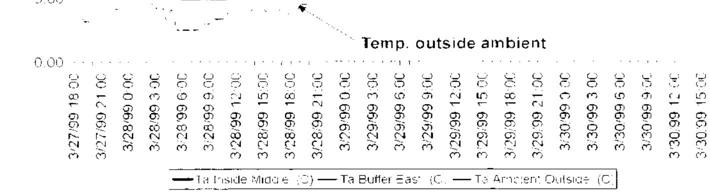

Fig. 6. Inside, outside and buffer temperatures for case without any element.

Data Collected with Aerogel Element

The introduction of a 20mm thick Aerogel element [see Fig. 7] showed clearly the effect of solar gain through the element. The interior temperature still followed the pattern of exterior temperature swings but at a significantly higher temperature level. Especially in the third series with five days of consecutive sunshine, the interior temperature was predominantly at least 5 deg. C higher on the interior then on the exterior. During midday this temperature difference was up to 10 deg. C, due to the high solar gains at this time. Temperature levels already too high for a comfortable indoor situation were reached by midday. The insulating effect of the Aerogel also prevented excessive heat loss through the glass so the temperature on the inside was at night significantly higher than on the exterior. The buffer on the other hand showed the same thermal behavior as in the initial measurements, displaying the low amount of heat transfer between buffer and control space.

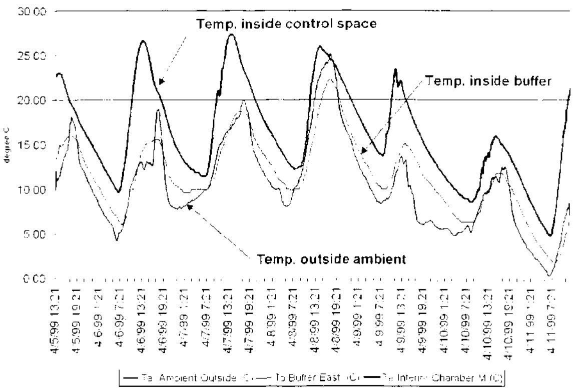

Fig. 7. Inside, outside and buffer temperatures for case with Aerogel element.

The illuminance measurements showed the effect of the exterior lighting condition on the interior light levels. Illuminance was measured on the surface behind the glass and on the ground in the middle of the test chamber. The light diffusing qualities of the Aerogel created a very even light distribution on the interior and the values in Lumen per square foot were almost identical on the surface of the element and on the ground. Maximum illuminance levels of up to 2000 L/sqm were recorded for the floor of the control space.

Data Collected with Aerogel and PCM Element

For the fourth and fifth measurement series, 20mm thick PCM elements were introduced as a second layer behind the Aerogel window. During these series the indoor temperature stayed again on a temperature level significantly higher than the exterior temperature. The internal temperature swings were effectively dampened by the thermal storage capacity of the phase change material [see Fig. 8]. As a result, temperature peaks on the inside were avoided and the inside ambient temperature changed within a 5 deg. C range while the exterior experienced greater variations. It could also be observed that in cases where the outside temperature changed very quickly the inside temperature changed more slowly due to the thermal mass of the PCM. In these cases, for the first time, inside temperatures were lower on the inside than on the outside.

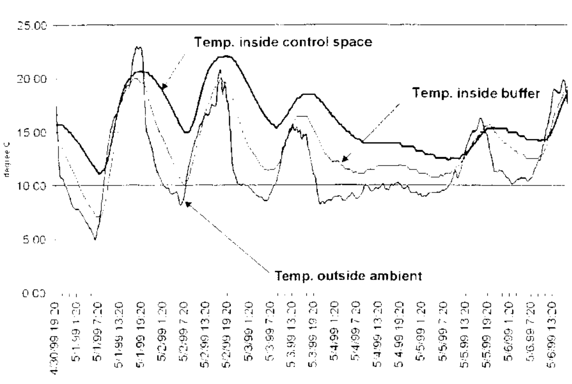

Fig. 8. Inside, outside and buffer temperatures for case with Aerogel/PCM element.

Due to the low solar transmittance of the Aerogel, not enough energy was gained to raise the temperature of the phase change material completely beyond its point of fusion. Therefore the thermal storage effect that was monitored is a combination of sensible and latent heat stored in the mass of the PCM material. It can be assumed that due to the high amounts of energy needed to achieve a complete phase change the inside temperature would very seldom rise over this temperature of fusion. Also the stored energy would keep the internal temperature for a longer period at a higher temperature. In continued measurements with a higher exterior temperature this effect should have become apparent.

With the introduction of the phase change material the illuminance levels on the inside changed dramatically. The surface sensor on the interior surface of the Aerogel window continued to detect high lighting levels, but sensor on the ground of the chamber detected significantly lower illuminance levels with a maximum of 500 L/sqm. This decrease is clearly caused by the additional layer in the skin and amplified by the fact that the PCM was mostly solid during the times data was collected. An increase in the visible transmittance due to a higher degree of phase transition can be expected and would occur at higher temperatures.

The measurement of surface temperatures of Aerogel and PCM showed that the surface temperatures on the inside of the element changed similarly to the interior ambient temperature. Compared to the case with just the Aerogel window installed, much higher inside surface temperatures and smaller variations in these temperatures were detected. With the investigation of surface temperatures it also became apparent that the speed with which heat travels within the phase change material is very high and that there is no time lag as in other heavy mass storage materials. This effect is caused by the high density of the storage material as well as by the thinness of this layer. Energy collected by the storage material is thus instantaneously available for the interior.

Conclusion from Experimental Evaluation

Measurements taken from the available samples in the test chamber allowed several qualitative conclusions. First, the data revealed that the introduction of a translucent storage element as it was proposed raised the interior temperature of a space. Even thin layers (20mm) of Aerogel and PCM kept the interior temperature at a significantly higher level (5 to 10 deg. C) while still providing a limited amount of visible light transmission. Next, the introduction of the PCM into the envelope construction effectively reduced diurnal temperature swings and created a more stable indoor temperature. Finally, the higher and more stable inside surface temperature of the PCM element contributed to an improvement in indoor comfort.

If the PCM material would absorb solar radiation at a higher rate, then the point of fusion could be reached, and the beneficial effects of such an assembly should be even greater. For example, an Aerogel with higher solar transmittance would increase the rate of absorption of solar energy in the PCM so that a more stable indoor comfort level would be achieved. Based on the data collected and previously established knowledge about potential improvements, this concept can be used to significantly lower the energy required for heating. Likewise, in areas with extreme diurnal temperature swings the damping effect of the PCM can also be used to reduce the energy required for cooling.

SUMMARY AND OUTLOOK

In light of the rapid consumption of the earth's fossil fuels and related problems of CO2 emission, major changes in energy use patterns in modern buildings must take place if massive environmental problems are to be prevented. The evaluation of the prototype revealed the potential of an assembly that can reduce the energy consumption required for heating buildings. To achieve this energy reduction, the proposed assembly utilized new materials and a strategy of active solar control. Moreover, even more significantly, through this new strategy the building skin takes on new functional and aesthetic qualities.

Challenging Existing Design Paradigms

The concept of the building as an active organism that provides optimal shelter with minimal energy consumption, is a fundamentally different design paradigm that will challenge designers and occupants. New design qualities could become the driving force behind innovative building technologies. In a context where affordable energy is too readily available, new aesthetic qualities combined with environmental benefits are among the most powerful incentives to push energy-efficient technologies forward. For example, over the last decade, new façade developments in Europe the architectural qualities of double-skin glass façades supported the environmental building agenda.

To facilitate such changes, further research needs to be carried out to make new materials and technologies feasible and advance their integration. The chosen evaluation for the proposed assembly proved to be successful as an initial assessment of the new component. The data collected in the test chamber validated the beneficial impact of the proposed component on an interior space. Solar energy gains and stable indoor temperatures were observed as a result of the new façade strategy. Evaluation of the light quantity and quality transmitted through the new element was possible through observations in the test chamber. Based on this study, potential areas of future research and development can be identified.

Future Research Needs

From a materials perspective, the most crucial advancement needed to further the ideas explored in this study is the development of stable and effective phase change materials. Research in this realm of material sciences almost stopped completely in the early 1980's and some of the most interesting opportunities for new ideas are still unexplored. Other developments like improvements in electro-chromic glass, Aerogel, sealant technologies and containers seem to make slow but steady progress and are well beyond the point of fundamental research. Now well-focused product development is needed to bring these materials from the laboratories to the construction site. In this context designers and engineers have to play an important role to determine feasible specifications that make use of the most advantageous material properties. They need to step beyond the boundaries of conventional construction and challenge preconceived notions o the building envelope.

From a systems and energy point of view, better tools to evaluate the performance of such advanced skins are needed. For the initial evaluation, the chosen method of experimental testing and preliminary calculations seemed appropriate. However, computational tools that allow for a precise assessment of the impact of advanced material composition and control strategies on a building's energy use and thermal performance are desperately needed to reduce time, risk and cost associated with the development of innovative applications. Such tools would support and validate the work with experimental test configurations although not eliminate the need for physical testing. In the process of this project the actual work with the prototype in the test chamber, its construction, integration and appearance provided valuable insights to a degree that alone made the enormous efforts for its construction worthwhile.

REFERENCES

Beck, A,. W. Körner, and J. Fricke. "Optical Investigation of Granular Aerogel Fills," Journal for Physics, D: Applied Physics, vol. 27 (1994): 13-18.

Dawson, Layla. "Light Spirited," Architectural Review 197 (January 1997): 20-21.

Lane, George. Solar Heat Storage: Latent Heat Material. Boca Raton, FL: CRC Press, 1983.

Kienzl, Nico. "Advanced Building Skins: translucent thermal storage elements." M.S. Thesis, Department of Architecture, Massachusetts Institute of Technology, 1999.

Manz, Heinrich. "Sonnenstrahlungsbeladene Latentwärmespeicher in Gebäudefassaden." Diss. ETH Nr. 11377, Eidgenössische Technische Hochschule, Zürich, 1996.

Marko, A., and P. Braun. Thermische Solarenergienutzung an Gebäuden, Frauenhofer Institut für Solare Energiesysteme. Berlin: Springer Verlag, 1997.

Rottkay, von K., M. Rubin, and J. Kerr. Optical Modeling of a Complete Electrochomic Device. Berkeley, CA: Lawrence Berkeley National Laboratory, 1996. LBNL-39594.

Sullivan, R., M. Rubin, and S. Selkowitz.. Energy Performance of Prototype Electrochromic Windows. Berkeley, CA: Lawrence Berkeley National Laboratory, 1996. LBNL-39905.

Wittwer, Volker. "3: International Symposium on Aerogels: Development of Aerogel Windows." Journal of Non-Crystalline Solids, Vol. 145 (1992): 233-36.