Advanced Building Skins
Translucent Thermal Storage Elements

by

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ABSTRACT

Advances in the material sciences continue to provide designers with a wealth of new materials that challenge preconceived notions of the building envelope and its performance. These new technologies can be used to create new adaptable building skins and allow for an active interaction with the environment to reduce energy consumption in buildings. This thesis investigates the function of the building enclosure in relation to these new material developments and recent changes in the treatment of the building envelope. New glazing, insulation and thermal storage technologies are discussed in the context of their technical trajectories.

Based on this discussion of functions and technologies, a specific set of materials is selected and their combination into a facade panel is proposed. This new element is a layered facade component including electrochromic glazing, aerogel and a phase change material. The combination is analyzed for its potential as a translucent thermal storage wall in the context of American residential construction. Aspects of performance, integration and design are explored through calculations, experimental testing and the creation of scaled models and a prototype element. For this purpose an environmental test chamber has been built on MIT's campus to evaluate the performance of new facade elements.

The result of this study shows the potential for such innovative facade concepts and points towards areas of future research to make such concepts technically and economically feasible. In particular, the need for better tools to evaluate the performance of such advanced skins is identified in order to achieve successful implementation of these new technologies and ideas.

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ADVANCED BUILDING SKINS
TRANSLUCENT THERMAL STORAGE ELEMENTS

TABLE OF CONTENTS

ABSTRACT

ACKNOWLEDGMENTS

1. INTRODUCTION 8

2. THE BUILDING SKIN 14
   2.1. Function of the Building Skin 19
   2.2. Building Skin and Energy Balance 22
   2.3. Development of Building Skins - Systems and Materials 24

3. NEW MATERIAL DEVELOPMENTS 32
   3.1. Glazing 34
      3.1.1. Summary 34
      3.1.2. State of the Art 40
      3.1.3. Future Developments 43
         Gasochromic Systems 43
         Suspended Particle Displays 44
         Electrochromic Glazing 46
3.2. **Insulation**  
3.2.1. **Summary**  
3.2.2. **State of the Art**  
3.2.3. **Future Developments**  
   - Regenerative Insulation Materials  
   - Gas Filled Panels  
   - Aerogel  
3.3. **Energy Storage**  
3.3.1. **Summary**  
3.3.2. **State of the Art**  
3.3.3. **Future Developments**  
   - Phase Change Materials  

4. **THE PROPOSED COMPONENT**  
4.1. **Strategy of Evaluation**  
4.2. **Description of Assembly**  
4.3. **Base Case Analysis**  
   - Critical Parameters  
   - Steady State Evaluation  
   - Spectrophotometer Measurements  
   - Building Heat Load Calculation  
   - Test Chamber Measurements  
4.4. **Application and Integration Implications**  
   - System Implications  
   - Failure Modes  
   - Place Response  
   - Construction  
   - Cost Assessment
1. INTRODUCTION

The international discussion about the depletion of fossil fuels and the related pollution caused by the combustion of these fuels for the generation of thermal or electric energy has caused an increased awareness of the impact of energy consumption for the creation and operation of buildings. Studies show that 50% of the energy production in industrialized countries is used for this sector (see figure 1). These developed countries account for twenty-five percent of the world population and currently use eighty-three percent of the global energy production. Thus a clear connection between energy consumption and level of industrialization can be established. Trends indicate that as a country becomes more sophisticated its energy consumption follows patterns similar to those established in North America and Europe. These trends have enormous implications when they are considered in the context of the exponential growth in the world population (see figure 2). The implications are even more ominous when one considers the economic development and with that the adoption of Western technologies in countries like China or India. Their development will potentially lead to a rapid increase of the rate of depletion of fossil fuels. This will lead to massive environmental problems if major changes in energy use patterns do not occur in the next decades.

Energy Consumption and Environmental Implications

The potential outcome of such environmental changes have been discussed and published consistently in recent years. International conferences, such as the

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1. see Daniels, page 20
2. see publications of the World Watch Institute at http://www.worldwatch.org

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1992 Earth Summit in Rio de Janeiro\(^3\) and in 1998 in Kyoto have been held to attempt to build consensus around strategies to counteract these developments. Unfortunately, the main industrial nations have not yet made the commitment to make significant and necessary changes in their energy policy. North America is the region with the highest energy consumption per capita (see figure 3). Energy prices are currently at a twenty-five year low (see figure 4) and the economic short term benefits for reduced energy consumption are virtually non existent. This situation reduces the argument for increased investment in low-energy technologies or strategies to improve the long-term implications for health and environment. Even if an increased environmental awareness in the population starts to create a receptive situation for these new strategies, the economic benefit for consumers and industry is not yet great enough to be a strong incentive to rapidly implement such changes. Nonetheless, some changes have been initiated by policy makers and planners, for example in Germany and Scandinavia, where the cost of energy is high and environmental changes more apparent.

In this discussion it needs to be clear that currently the main concern is the rapid increase in the CO\(_2\) concentration in the atmosphere. This increase is caused by the vast and increasing combustion of fossil fuels mainly in the developed world. This increased concentration of CO\(_2\) has been identified as the source for global warming and is generally referred to as the greenhouse effect. Evidence for, and potential implications of, global warming have been studied and published in the last decades. Especially these anticipated implications of global meteorological and climate changes have led to an increased awareness in the political arena

\(^3\) see Johnson for a summary of the 1992 United Nations Conference on Environment and Development (UNCED)

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for the need to counteract these developments\(^4\). The building sector has been identified for its potential for significant reduction in its related CO\(_2\) emissions. This reduction has the potential to be as high as ninety percent for the creation and operation of building’s\(^5\).

New Strategies

Although the economic benefits are yet to be created for more significant policy changes, the dramatic prognoses of the potential outcome of our current use of energy makes it worthwhile to generate ideas and technologies to further such developments. The building industries with their high percentage of the total energy consumption, can be identified as a sector of high priority for such new strategies. A significant decrease in the energy needed to construct and operate buildings will have a recognizable impact on the environment. The building industry should be at the forefront of an heightened environmental awareness also for another reason. Since buildings are an important and integral part of our culture, changes in the technology and attitude that influence this built fabric will have intellectual and cultural implications for the people who use it. Therefore, a change in the very nature of our built world, and how one interacts with it, might be able to trigger more significant changes in the way available resources are treated. This could even effect what is expected from other products and services. The cultural context is an important factor to acknowledge in the approach to the problems being faced. Recent examples for low energy buildings showed that solutions need to be integrated into this context to be successful beyond a pure performance level. Projects designed by Thomas Herzog (see

\(^4\) see Vice President Albert Gore’s book “Earth in the balance”, as an example for the call for increased political awareness and changes in energy policies

\(^5\) see Energiegerechtes Bauen und Modernisieren, page 14-16

Advanced Building Skins - S.M. Building Technology - N. Kienzl - School of Architecture - MIT '99
image 1) and William McDonough (see image 2) display how designers and engineers must play leading roles to transform technical concepts into feasible realities and improve the quality of inhabited spaces.

Part of the process of generating such new solutions includes evaluating existing and emerging technologies. New combinations and approaches also need to be explored. Of special interest is the rapid development of the field of material sciences. It continues to provide designers and engineers a wealth of new materials and technologies that challenge the contemporary understanding of material properties in buildings. These advanced materials have the potential to transform the expectations of the performance of buildings as well as the appearance. The transfer of these materials from scientific laboratories into the construction industry needs to be guided by thorough studies of the advantages of these materials. The evaluation of their potential applications should serve as an important guide for new developments or research endeavors to further tailor materials for use in the construction industry. Here again, the performance of a new technology needs to be evaluated in the context of the built environment and all related implications.

The Thesis Approach

This thesis presents such an evaluation process. Focusing on the building envelope as the physical enclosure of the building, a set of new materials is analyzed and a new enclosure assembly proposed. This assembly is evaluated in the context of American residential construction. The implications of its use on the energy consumption, its integration and appearance are evaluated. This study investigates the application and use of this new element within the design process and the systemic connections.
The second chapter introduces the building envelope, the skin that encloses buildings, its principal functions, parameters and performance criteria. The relationship between the construction of the envelope and the energy consumption of the building is outlined and examples for new approaches for the design of the enclosure are presented. This chapter serves to build the rational for the materials selected for the proposed assembly.

The third chapter discusses particular set of material developments relevant to the envelope. The historic evolution of glazing, insulation and energy storage materials are presented and their performance characteristics are investigated. An overview of the state-of-the-art of these technologies is given as well as an outlook into future developments.

A new facade panel element is introduced in the fourth chapter. The performance of the element is determined by means of calculations and physical testing. For this purpose a test facility was erected on MIT's campus. The rational for the test setup is presented in this chapter. Implications on the energy consumption of a residential structure, derived from the performance of the element, are discussed. The integration of the element into residential construction is evaluated with respect to construction as well as architectural design.

The fifth chapter concludes the thesis with a final evaluation of the determined benefits and challenges of the proposed element. It serves as an view into the potential for future improvements in the investigated materials and the applicability for the design and construction of the building envelope. This conclusion also attempts to answer the "so what?" question. It establishes whether the increased cost and effort in the creation of such an element is
justified from an energy savings standpoint or whether other qualities of such assemblies could increase their feasibility and acceptance.

This work represents a research project within the *House_n: MIT's Home of the Future* research consortium, which investigates the future developments in residential architecture. It was therefore the prime concern to analyze a wide range of new developments to find future venues and trajectories for the design of buildings and to outline feasible paths corporations and research institutions could follow in order to transform the industry.
Thus man was compelled to invent architecture in order, ultimately, to become man. By means of it he surrounded himself with a new environment tailored to his specification, interposed between himself and the world\(^1\).

The ability to mediate environmental forces may be the most crucial ability of the human species and vital for its survival. There are very few locations in the world that the human organism would alone be able to exist within the climatic and atmospheric conditions. Unlike other creatures, the human body is only able to adjust its exchange of energy and matter with its environment just to a very narrow range of conditions without harm. The range is even narrower to feel comfortable. The achievement of these conditions, or finding equilibrium, is and has been the one of the primary concern of human activity.

Protection of the Body

All throughout human history two different approaches to achieve this protection were invented and developed. The first approach was the protection of the individual body by surrounding it with layers of fabric. From the first fur coats to the space-suits and high-tech sportswear of today, the purpose of these layers was to mediate specific environmental conditions for an individual body. This approach sought to accommodate the general or specific activities that the individual needed or wanted to carry out. A wealth of different types of layers has

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1. See Fitch, page 16.
been available and they have been more or less consciously utilized to adjust to climate, activity and social context. These fabric coverings created a micro-environment that surrounded individuals creating comfortable contexts for the body’s metabolic and perceptual systems.

Enclosure of Space

The second approach was the enclosure and protection of space through buildings or architecture. This second strategy was fundamentally different from the layers of clothing. In this case, an interior environment was created in which individual bodies, goods and processes were sheltered from the exterior and natural elements. This shelter created a meso-environment\(^2\) that mediated environmental forces enabling social interaction between individuals and the execution of tasks and processes that defined cultures and societies. Through this physical intervention with the world, humans were able to attain the high level of sophistication in culture and technology.

The fundamental differences between clothing and architecture are their differences in physical configuration, permanence and adaptability. Despite this, they also share common aspects. The purpose of both of these strategies is to transform the continuously changing environmental conditions of our planet to an acceptable set of conditions for the human body. Thus, both of them have a direct relationship with the natural or macro-environment as well as the metabolic, perceptual and muscular/skeletal system that defines a person’s physical interaction with the world. A deep understanding of this relationship is necessary to create successful solutions and a situation in which one can not

\(^2\) for a closer definition of meso- and microenvironments in this context see Fitch, page 15

Advanced Building Skins - S.M. Building Technology - N. Kienzl - School of Architecture - MIT '99
only survive, but also be comfortable enough to be productive, creative and socially active.

Over the last century, ironically through vast technical improvements, the understanding of this relationship and the role of architecture in its natural context has diminished. With the availability of technical support systems to artificially condition interior spaces our buildings have become less responsive to the environment. Designers concentrated on issues that were initially secondary to the creation of efficient shelters. Thus, style, construction technologies and cost became dominant design criteria and the interior environment was adjusted by the addition of artificial lighting and conditioning systems. The drawbacks and inherent problems with these artificial systems become increasingly apparent with our increasing ability to monitor and evaluate indoor environments. Indoor Comfort and "Sick Building Syndrome" have become new key words in the professional vocabulary.

The Building Skin

The building skin is the ultimate barrier between the interior and the exterior. It has become less responsive to site and climate conditions over time. With the global adoption of certain technologies and style elements, like the curtain wall facade, the creation of a comfortable indoor environment became dependent upon the use of increasing amounts of energy for new technical subsystems. This development was driven by a variety of technical, economic and cultural factors. It has also led to an increased detachment of building design from actual environmental conditions. Just in recent years, initiated by the oil crisis in the 1970's and an evolving understanding of the implications of the use of these technologies, designers have started to question this strategy and to shift their
The environmental influences that affect the design of the building skin as illustrated by Fitch

Many contemporary works attempt to reassess the relationship between the exterior and interior environments and the building's configuration. These "new" strategies return to the initial understanding of the building as a mediator of natural conditions. There is the intention to use these climatic conditions in creating the desired interior situation. In doing so, aspects of energy consumption are addressed as well as issues of indoor air quality, visual comfort, thermal comfort, and general perception as well as experiential qualities. Understanding the conscious interaction between the individual and the environment via the medium of the building becomes increasingly critical in the building design.

In this context, the building envelope, the skin and enclosure of the building, becomes increasingly important. It is, with the structural system, the most important sub-system in a building since it controls the flux of energy and matter into and out of the protected space. It becomes the key element for responding to environmental conditions. These conditions can be separated into two types: those that change and those that are constant. Special emphasis is placed on facades and materials which can change their physical properties in response to macro environments. Important aspects of a building's success lie with its interaction with local conditions (i.e. the position of the building, the shadows of neighboring buildings or the geographic conditions). These aspects should have a great influence on the choice and orientation on the site, as well as on the configuration of the structure. However, the great majority of environmental forces in most climates are constantly changing. There are diurnal ambient temperature swings, changing light conditions due to changing meteorological or seasonal variations and varying amount of precipitation or wind. The physical forms of buildings are, unlike clothing, not easily reconfigured. Their ability to

Advanced Building Skins - S.M. Building Technology - N. Kienzl - School of Architecture - MIT '99
adjust to changing environmental conditions is limited. Nonetheless, the building skin can be designed in a way that allows for a certain amount of transformation and variation to adapt to these changes. Thus, the variation of the buildings response brings the larger environmental context back into the forefront of the perception of the inhabitants on a daily basis.

The overriding paradigm for a successful design must be found in the thorough investigation of local conditions and the development of a site specific design solution. Unfortunately, most architects and engineers have lost much of their ability to find such solutions. Their education and practice tends to encourage the design of buildings that use energy to modify, instead of adapting to, their local conditions. Even when designers try to work towards the goal of a responsive building they often fall, due to lack of knowledge or resources, into the trap of copying existing solutions from other part of the world. Often these solutions are not appropriate for their situation and the building again requires large amounts of energy to counteract an inappropriate strategy. This situation is especially difficult when solutions are copied for their visual appearance. For example, many of the current double glazed facade systems in Europe are applied indiscriminately throughout the continent with a serious lack of understanding of the performance implications of such a technology. In recent years, the acknowledgment of the importance of an appropriate design strategy and its relevant information have led to research efforts that build a framework in which such design process can be successfully developed.  

Therefore, a successful application of new technologies to the building envelope demands an understanding of the functionality of the envelope. Thus, it is

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3 see in this context the Sol-Arch-Data project for the integration of research results and scientific findings into the design process and architectural education. This project was carried out by the chair of Prof. Thomas Herzog at the Technical University Munich and supported by the European Union.
necessary to clarify the functional parameters under investigation in each case. These are mapped with associated performance parameters in this work with their implications on the overall system performance.

2.1. Function of the Building Skin

A study of the building skin should clearly define the aspects of the envelope under investigation. The building envelope, as the barrier between the interior and exterior, includes all surfaces that make up this boundary and is continuous in all orientations (see figure 6). This includes surfaces below and above ground as well as horizontal and vertical surfaces (see figure 7). These surfaces are exposed to very different environmental forces and therefore have very different requirements. Even the same group of surfaces, such as the vertical walls of a building, have different constraints based on their orientation and the function of the interior spaces. These requirements need to be addressed individually for a successful treatment of the building envelope. The transformation of one surface into another is in many cases the most difficult aspect of the detailing and construction.

It has been found that about forty percent of the primary energy consumed in industrialized countries is used to produce low temperature thermal energy for heating dwellings and industrial buildings, domestic hot water and low temperature industrial process heat⁴. In this context, it becomes clear that the reduction of heat loss of this low temperature energy would have a major impact on overall energy consumption. Thus, solutions to decrease the heat loss and to increase the use of solar thermal energy become very important. In a typical residential construction, around sixty percent of the primary energy is lost

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⁴ see Wittwer

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through the vertical walls, including opaque and transparent elements, and ventilation. Energy loss through roof and basement at twelve percent is comparatively minor (see figure 8)\(^5\). The high percentage of energy lost through the vertical wall can be explained by the larger overall area of the wall compared to the smaller areas of the roof or floor in standard building design. Also, the wall is normally not shielded by buffer zones like unheated cellars or attics in the case of roofs and floors.

The criteria that affect the building envelope can be organized into six categories: *Building Function* Location/Exposure, *Surrounding Conditions*, *Functional Components*, *Structural Requirements*, *Energy and Environment*\(^6\). These groups contain a complex set of sub-issues. Performance requirements for each of these issues have been defined by common standards or experience. These standards define the performance of the building's needs, such as protection against structural or moisture damage, and the needs of the inhabitants. In particular, the requirements for indoor comfort of the inhabitants have led to an exploration of the range of conditions that are acceptable or desirable\(^7\).

The thermal performance of the envelope becomes the predominant factor in reducing the energy consumption of buildings. In addition, solar radiation can be used to reduce the heating load as well as the need for artificial lighting. Both thermal environment and solar radiation are forces subject to significant diurnal, meteorological and seasonal changes. So far, attempts to deal with these forces have been limited to designing for a worst-case scenario. Limited success has been achieved in creating responsive technical solutions as discussed later in this text.

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\(^5\) as published by the German Bundesarchitektenkammer in *Energiegerechtes Bauen und Modernisieren*

\(^6\) see definition and examples in Ragonesi, page 6-7

\(^7\) for an early example and an in-depth discussion of these conditions see Fitch
This thesis focuses on the exploration of potential improvements to the thermal and luminescent performance of the building envelope based on the selection and combination of new materials. Although issues like ventilation, filtering of environmental particles, protection against intrusions and other aspects of the building envelope mentioned before are important, they are not explored in this discussion. This investigation explores a non-load bearing element so the issue of structural performance is not addressed.

This thesis proposes the development of an element that allows for a new understanding of the enhanced ways that the building skin can function by allowing for changing material properties and the use of high performance materials. The idea of the building skin as a functional skin, similar to the adaptive skin of a chameleon, is the driving concept for this work. It has been strongly influenced by the search for a polyvalent wall, a wall that is able to adjust to many environmental conditions, as proposed by Mike Davies⁸ (see figure 9). His scenario of the performance of an imaginary wall is still one of the strongest visions for the wall:

"Look up the spectrum-washed envelope whose surface is a map of its instantaneous performance, stealing energy from the air with an iridescent shrug, rippling its photogrids as a cloud runs across the sun; a wall which as the night chill falls, fluffs up its feathers and turning white on its north face and blue on the south, closes its eyes but not without remembering to pump a little glow down to the night porter, clear a view-patch for the lovers on the south side of the level 22 and to turn 12 percent silver just after dawn."⁹

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⁸ see Davies for an introduction to the concept of polyvalent walls
⁹ see Davies
2.2. Building Skin and Energy Balance

The goal of heating and cooling is the creation of a comfortable indoor climate. The parameters that define a comfortable indoor situation depend on a variety of factors. Apart from physiological aspects like activity, clothing and metabolism of the occupant, other aspects like time of day, season and even cultural preferences play an important role. The human body uses all three forms of heat transfer to keep the body at a constant temperature and its metabolism intact: radiant exchange through the skin with other surfaces, convection with the surrounding air, and conduction via evaporation. These processes are affected by surface temperatures of the surrounding elements as well as temperature, speed and humidity of the air. At higher temperatures, humidity becomes increasingly important, since evaporation becomes the main form of heat transfer and is directly affected by the relative humidity. These factors shape the range of conditions that are ideal for human comfort. Energy consumption for heating and cooling is directly connected to how narrowly this range is defined.

The maintenance of a building’s energy balance relies on internal and external factors in order to determine the actual needs for heating and cooling. Main factors are the heat generated by occupants and equipment, heat lost or gained via convection, ventilation and conduction through the building skin as well as radiant heat transfer with the environment. The optimal result of such an energy balance would be the zero energy house where all gains and losses balance to result in zero at all times, so that no energy needs to be supplied or extracted by heating and cooling processes. Since all of these internal and external factors are subject to continuous change, the zero energy state is almost impossible to achieve.

10 as an early example see Fitch, for a more recent discussion see Ragonesi
Achieving a low energy balance is especially difficult if a building cannot adjust to changing conditions and is not able to absorb and release energy at different times. This flexibility has been applied through the introduction of variable elements and thermal storage devices. Variable elements can be operable openings that allow for a change in ventilation, blinds that allow for a variation in radiant energy transfer or shutters that decrease the convective heat transfer. The storage of thermal energy can be achieved through the introduction of elements with a high mass that need to absorb large amounts of thermal energy to raise their temperature. This strategy can be used for the building envelope as well as for the internal mass of the building by introducing heavy mass building elements. Based on the time lag in such elements, thermal energy can be stored to mediate diurnal temperature swings.

In most climates these two approaches can be effectively combined to reduce the energy consumption of buildings. For example, in a summer situation cold night time air can be used to cool down thermal mass for the day and blinds can facilitate the reduction of solar input during the day. The building skin is in this context the most critical building element. Except internal loads through occupants and equipment, all aspects of the energy balance are related to the performance and operation of this boundary. If the performance of the envelope is not sufficient to create the desired indoor environment, external energy must be supplied in order to heat, cool and ventilate. Thus the nature of the skin of a building is directly related to the sizing, layout and energy consumption of most other building systems and improvements to the skin can have far-reaching implications for the building design and its employed technology.

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11 for a history of such strategies see Butti
2.3. Development of Building Skins - Systems and Materials

Most buildings are designed to use standard technologies for the construction of the building envelope which are based on traditional means and methods. These technologies have improved slowly in recent years with bigger jumps found where codes or regulations increased the prescribed requirements. Designers usually use these technologies with little knowledge about potential improvements and the principles behind them. Unfortunately, these designers make up the largest group of the profession. Even through better implication of existing technology the energy consumption of buildings could be reduced. However, most designers and clients are more concerned with issues of initial cost, speed of construction, reduced planning time, and appearance. Only a small group of designers, clients and engineers are interested in stepping beyond established solutions to search for innovative design solutions to pressing environmental issues. These designers face the difficult task of developing better solutions at competitive cost and on schedule. The design cost, including the cost of engineers, researchers and producers, associated with these developments is a major concern and obstacle. Thus, the development of new solutions primarily occurs with signature commercial buildings designed by firms with a strong background in technology. Hopefully, the lessons learned in these projects will provide guidance for projects with smaller budgets and establish new means and methods for the industry.

During the last two decades interesting new solutions for the design of the envelope have been generated in Europe. The innovative role Europe plays in this development is only partly caused by a different approach to building cost and a bigger environmental awareness. Also, these construction and subsequent publication of these constructions established a strong aesthetic trend. The more prominent examples of these projects often focus on special aspects of
performance. In the context of this thesis, some of these examples are mentioned to give an overview of new design directions and to provide some background for potential developments in residential design. These examples have been grouped together by the areas in which they were intended to make the biggest improvements.

Reduction of Solar Gain

The biggest problem in commercial buildings is associated with excessive solar gain that results in an increased cooling load and glare. A successful example for the introduction of exterior louvers as shading devices is the Construction Office Gartner, designed by the architecture firm of Kurt Ackermann\textsuperscript{12}. This building uses semitransparent and partially reflective glass louvers on the exterior to control solar heat gain and enhance visual comfort. The coating of these louvers not only provides shading but also allows a degree of visual connection with the outside through the louvers. Another effect is the reflection of light into the building. The position of the louvers allows for light to be reflected against the ceiling of the office space and to produce a uniform light distribution even in areas in the depth of the building. The louvers are controlled by a central building system and react to the changing position of the sun. This system is very well integrated into the overall building design and provides interesting aesthetic effects by the varying reflections on the louvers. Such systems are advantageous because the heat is kept outside of the building envelope through the exterior location of the shading devices. The disadvantages of this system are typical for most louvers systems and are the high maintenance and installation costs.

\textsuperscript{12} see Peters and Ackermann

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To reduce this exposure of the shading devices to rain or wind some attempts have been made to integrate reflective shading elements into the building envelope. An interesting but also problematic example for such an approach is the facade of the Arab Institute in Paris, designed by Jean Nouvel\(^\text{13}\) (see image bc). Here the shading elements have the form and function usually found on a different scale in camera shutters. These reflective shutters are enclosed within the glazing of the skin and are therefore not exposed to the environments. They are mechanically controlled and can adjust to exterior light and indoor requirements by a gradual opening and closing of the shutters. Conceptually this idea is very interesting because it creates a self-contained responsive facade. The disadvantage is that it is a very complex device that is prone to mechanical failure. Also, the unique nature, high complexity and number of parts of the system makes it an extremely uneconomical solution. If a similar concept could be realized with a simpler construction and at lower cost this concept would be an interesting alternative to exterior shading elements.

A similar desire to moderate solar gain within the skin has led to the development of materials and systems that reflect certain directions of the solar radiation. These systems of fixed, angular selective shading devices usually do not allow for changing properties. This reduces their effectiveness but also decreases their cost and chance of failure compared to mechanically operable elements. The most striking example of such technologies are micro sun shielding louvers (see image). These aluminum coated plastic grids are designed in a way that they reflect direct sunlight and allow for diffuse light to pass. These grids can be enclosed in the depth of conventional double glazing and are highly effective in the reduction of cooling loads. The development of this technology was led by the lighting engineering firm of Christian Bartenbach in Austria, the design Firm

\(^{13}\) see Campagno, page 88-89
of Thomas Herzog and Siemens Beleuchtungstechnik as producer of the elements. The first installation of this technology was in the roof of the Design Center Linz, designed by the firm of Prof. Herzog\(^\text{14}\) in which the whole curved roof structure of an extensive conference and exhibition center was covered with these composite elements. The disadvantage of this technology is that the units are neither transparent nor uniformly translucent but show a complex pattern of reflections. This reflection makes the system a very interesting solution for skylights and roofs but very difficult for vertical walls.

Natural Ventilation

The ability to naturally ventilate interior spaces is taking on a larger significance as clients demand solutions to overcome the comfort and energy problems associated with fully air-conditioned buildings. To accommodate this desire to be able to open a window and let air in is a complicated task in the sophisticated systems current buildings represent. Especially in commercial high rise buildings which are exposed to higher wind pressures on the facade this has not been a technical possibility until now. In recent years naturally ventilated double layered facades have been introduced to break down the wind speed and to create a controlled air pressure situation. This concept has seen many variations in the way the two layers are arranged and how the airflow is controlled and distributed.

In the example of the Duesseldorf City Gate Building, designed by the architect Petzinka, Pink and Partner a very deep version of such a double facade has been chosen\(^\text{15}\). The outer layer of this sixteen-story office building consists of large panes of single glazing while the inner layer is made of double-glazing in

\(^{14}\) see Herzog, pages 145-155 and 201
\(^{15}\) see Herzog, page 124-125

Advanced Building Skins - S.M. Building Technology - N. Kienzl - School of Architecture - MIT '99
wooden frames. The two layers are spaced approximately 1.25m and create on each floor a continuos buffer space around the building. Controlled by a central building system mechanical ventilation openings control the air intake into this buffer on each floor and the inhabitants can open their interior windows individually to condition their offices to their needs. This system also serves to break down the noise from the highway traffic the building is exposed to and contains reflective shading devices within the buffer. The designers claim that the building is in this way able to operate within a temperature range of \(-12^\circ\text{C}\) to \(+28^\circ\text{C}\) without additional energy for heating and cooling.

The advantage of such an arrangement of the two layers is that through the continuos buffer around each floor, fresh air can be supplied to all sides of a building and through the correct use of openings in respect to outside conditions even cross ventilation of the buffer is possible. The disadvantage is the increased cost and increased complexity of such systems. However through improved controls and a cost clever selection of detailing and materials this approach is becoming a feasible solution.

A similar approach, even with a very different arrangement, is the office tower for the Commerzbank Headquarters in Frankfurt/Main, designed by Sir Norman Foster and Partners\(^\text{16}\). In this sixty story high-rise two different schemes of natural ventilation are used. One is the large scale cross ventilation of open gathering spaces and the central core throughout the building. The second approach is more relevant to the here discussed topic and is the natural ventilation of the individual office spaces through a layered window arrangement. In the construction of the windows a single pane of glass is mounted in front of a conventional double pane window with 0.15m spacing. This frame of the outer glass pane has small openings on the top and bottom of each window to allow

\(^{16}\) see Herzog, page 108-109
continuous air supply into this buffer space. Within this gap small reflective retractable blinds are installed as shading devices. Each floor and window is separated and there are no mechanically controlled devices. This arrangement serves to break down wind speed and noise and protects the fragile louvers.

The advantage of this system is that it is comparatively simple and intuitive and does not need any extensive controls which reduces cost and complexity. It is anticipated that the use of these windows increase the indoor comfort by giving the inhabitants access and direct control of their air supply. The disadvantage might be that this system can not counteract differential pressures on different sides of the building and positive and negative pressures on the facade can create very different indoor situations.

Through the use of new computational fluid dynamics software and increased computational performance these complex assemblies can be simulated and strategies can be tested before they are applied. These tools supplement the traditional means of wind tunnel testing to predict the airflow in and around buildings at much lower cost.

**Thermal Mass / Solar Storage Systems**

The use of new insulation materials, discussed later in this text, led to the design of projects that made use of brick or concrete construction to capture and store solar energy to reduce the internal heating load. The use of these technologies for smaller and heating dominated buildings and regions has produced some interesting results and showed new trajectories for solar architecture. In this new approach towards solar architecture the traditional image of solar buffer zones and wintergardens is replaced by compact assemblies.
An example for such a new project is the Hostel for Youth Educational Institute in Windberg, Germany, designed by the Firm of Prof. Herzog\textsuperscript{17}. Here, the south facade is divided into alternating vertical segments of windows and opaque walls. The opaque elements are an assembly of sand-lime brick with an exterior layer of translucent insulation. This assembly allows for the gain of solar energy and the mass of the wall creates a time lag into the evening hours when the heat is needed inside the living spaces on the interior. To prevent the wall from overheating during the summer months, exterior louvers can be lowered to shade the walls. This situation creates an interesting shift in perception, since in a conventional wall one would not expect shading devices in front of opaque wall elements.

The advantages of such a system are clearly the low cost and the potential energy savings. Disadvantages are mainly in the need for exterior shading device and the related cost, control and maintenance issues.

Acoustic Properties

Especially in inner city areas the use of advanced facade technology has been used to reduce the noise from traffic or other urban or industrial sources. This noise is in many projects a primary concern and prevents the opening of the facade to the exterior. The use of additional layers in the building skin has been employed in recent projects to reduce this form of environmental impact. A recent example of such a strategy is the facade design of an office and housing project in Munich, designed by the firm of Steidle + Partner\textsuperscript{18}. Here the north and west facade of a larger building block faced a very noisy inner city street and were

\textsuperscript{17} see Herzog, page 66-67

\textsuperscript{18} see Herzog, page 122-123
clad with an additional layer of glazing. These glass panes, mounted in full story height steel frames, are located at a distance of approximately 0.4m from the main facade and serve as an acoustic buffer. This buffer is continuous over large parts of the facade and can be used for natural ventilation purposes as well. Usually such a configuration of a second layer is problematic since the heat that is generated in the double skin might create undesirable warm inside temperature on the top floors. In this special case, the orientation of the building and the moderate climate allowed for this configuration.

The advantage of such an increased acoustical performance of the building envelope can lead to reduced energy needs for mechanical systems. The high cost of such a facade however seldom justifies such a solution for acoustical reasons alone. In combination with natural ventilation and improved shading schemes these systems can become feasible solutions.
3. NEW MATERIAL DEVELOPMENTS

The creation of buildings is determined to a great extent by the technical choices available to solve a given design problem. Materials and production technologies are therefore primary influences on the design and performance of architecture. Throughout history it can be observed how new materials and technologies have been used to create new solutions for buildings\(^1\). These technical capabilities not only changed the way buildings are constructed but they also altered the function and form of buildings and became thus an expression of the abilities of a society and time periods\(^2\).

It is important to clarify the relationship of material to manufacturing technology. As physical matter from the environment, materials need not be invented. What is needed are innovative ways to manipulate existing materials into new configurations. Therefore everything that is referred to as a "new material" is based on a new technology to create new configurations or compositions. In the analysis of so-called "new materials" it is thus important to look at what the actual components of a new configuration are and what processes are required to create them. Both of these aspects are especially relevant if new materials are analyzed for their environmental impact. For example, the energy used for the creation of a new material has to be taken into account to assess the overall energy balance of a construction\(^3\). Also, the ways in which the ingredients of a material can be separated or reconfigured for future use is critical to assess its

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1. see Elliot on various examples for the development of construction materials and systems, and their influence on architecture.
2. for example the change in building heights that has been made possible through the invention of the elevator, see Elliot
3. see Steiger, SIA Dokumentation DO123
value in the larger cycle of matter. This process of analysis is complex and
difficult especially with new materials. Knowledge about the technology involved
in the creation of new materials is often the main asset of a company. Therefore
information is very reluctantly published in detail and the detailed assessment of
new technologies is difficult before it is officially tested and standardized.

Since the beginning of the industrial revolution, the knowledge of materials and
production technologies has increased dramatically and continues rapidly. In the
mass production of goods that was made possible by the industrial revolution,
this knowledge provided a competitive advantage for the producer. Thus a strong
incentive was created to further this knowledge in order to produce cheaper,
faster or better products. The fast successes in this development and ever-
growing financial benefits made research in material sciences a vital aspect of
economic growth. Advancements in the research of material sciences made it
possible to design materials for certain applications in ways that are
unprecedented. This enables designers to choose from a wide range of materials
to solve design problems. Such a wealth of materials can be created that there is
a need to specify up-front what improvements are desirable. The designer is
asked to clarify material properties for a certain performance so that research
can try to match these properties with new developments4.

To recognize the potential of new materials it is important to understand the
historical background, physical characteristics and technologies involved. This
understanding serves as a basis for design decisions, as well as for the
development of realistic expectations in the performance of new technologies.

For the building skin three groups of materials of particular importance are
discussed in the following section. These groups have been identified for their
ability to transfer (glazing), block (insulation) or store energy (storage materials).

4 see for example the design of new thin film or polymere technologies.

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Each of these material groups is an intensive field of study and is just briefly summarized in this text. However emphasis is put on the discussion of future developments and especially on the discussion of one key technology in each of the groups as an introduction to the proposed facade component.

3.1. Glazing

Historically glass has been of particular importance in the construction of buildings for its ability to transmit light and solar radiation into buildings while providing protection from external elements. This ability allowed for enclosures that are naturally lit and heated by solar energy. Glass has evolved through major changes in its production technologies in the last one hundred and fifty years making it a widely available and affordable building material. These changes have not only increased its range of applications but also inspired designers to create fundamental changes in building design. In the following text a short summary of its history and performance parameters is presented.

3.1.1. Summary

Initially discovered 4000 years ago in the eastern Mediterranean as a side product in the creation of pottery, glass was produced as a container for liquids and as jewelry in Egypt and Greece. It is assumed that the origin of glass in these hot climates prevented its early adoption as a material for the covering of wall openings. With the migration of glass production into colder climates of the Roman Empire its potential as a building material was discovered. Based on techniques adopted from the production of flat glass bowls, thin glass panes were produced to cover windows. Rich patrician Romans used glass to enclose
their buildings and to create small conservatories to grow plants. The production technique at that time was to melt silica sand and other ingredients and then to cast or blow the liquid glass into desired shapes. Through this technique a very uneven and thick glass was created.

The Growing Demand for Glass
With the spread of the Roman Empire to the north the use of glass increased and was adopted for the transparent envelope elements for buildings all through Europe. Important in the production of glass was the quality of the base material, silica sand, the extremely sophisticated labor involved, and the availability of large amounts of energy for the melting process. This led to the creation of glass centers throughout Europe where the resources were available and where the tradition of glass manufacturing provided skilled workmanship. The need for bigger and more even panes of glass led to the development of the crown process and further developments in casting glass. For the crown process a molten drop of glass was rotated in a way that the centrifugal forces would create a disk of glass. These processes allowed for bigger glass panes but still had the problem of uneven surfaces. To create a smooth surface it was necessary to polish the glass after it was cooled down. Both processes increased the maximum sizes of glass panes but were extremely labor and time intensive. Therefore Glass became an expensive building material that was used for special buildings like cathedrals and palaces.

During the Gothic period with its dematerialization of the stone wall glass was used for the first time as a major part of the building envelope. Here colored glass was used not only to protect the interior but also as a design element to heighten the spatial experience. This increased the demand for glass and led to
the development of the cylinder process, whereby glass was blown into the shape of a large cylinder whose ends where cut, then slit longitudinally and flattened. This process allowed for smoother surfaces and higher production output of glass panes.

The Industrial Production of Glass

In the following centuries glass became more and more a product for profane architecture. With the introduction of cast iron, steel and reinforced concrete into building construction the traditional load bearing wall started to disappear and glass became a material of choice for the enclosure of buildings. Especially in the United States where new cities literally exploded the demand for glass skyrocketed and producers tried to find solutions to mechanically produce glass. In 1896 John Lubber in Pittsburgh, imitating the traditional cylinder process successfully created the first of these machines. A couple of years later in Belgium Emile Fourcault developed a machine that approached the problem from a new angle pulling large panes of glass out of the glass molt over a series of rollers. This process reduced the production time and simplified the process but created a lower quality glass and still required intensive polishing of the panes. In the United States the Libby Owens Sheet Glass Company developed a similar machine in 1905.

These new technologies made large quantities of glass available and glass became an economically feasible building material for almost every purpose. Designers started to see this new availability of glass as an opportunity and the Modern Movement in architecture was strongly influenced not only by the material glass but also by the fact that industrial production made the extensive use of glass possible. The development of designs of fully glass-clad buildings
was the result of this new technology. The early curtain wall facades of the Bauhaus or the design schemes for glass towers by Ludwig Mies Van der Rohe are clear and revolutionary examples of this new design philosophy.

In 1959 Pilkington developed the float glass process and the final obstacles in large-scale production seemed to be resolved. In the float plant, glass is poured on a bed of liquid tin on which it floats through its cooling process. This new technology not only made large volume production of very large panes possible but it also created glass of precisely controlled thickness that did not need to be polished. This process became widely adopted worldwide and it is the current standard production technology for glass used in windows and created the material description of Float Glass.

Glass can be manipulated in a variety of ways during production or post-production. Three principle techniques can be identified. First, the addition of substances to the glass melt, changing the color, chemical resistance and strength of the material by changing its chemical configuration. The second is the manipulation of the glass surface, either during the cooling process or in its final state. The variations that can be created this way include the pre-stressing of the glass for structural or safety reasons as well as coating and coloring of the glass surface. Finally, the combinations of panes of glass with other materials opens up the applicability of glass for an even wider range of uses. This includes the lamination of glass panes or the creation of multiple layer compositions for insulated windows as well as for fire resistant glass or other special applications.

Chemical Characteristics of Glass

Glass is often referred to as a super-cooled liquid, because its production process is based on the melting of silica and a controlled cooling process that
prevents crystallization. Its molecular structure thus combines the characteristics of a solid and a liquid in the same material. Conventional float glass contains silica sand (SiO₂, 71-75%), soda (Na₂O, 12-16%), lime (CaO, 10-15%) and a small percentage of other materials which have an effect on the color (e.g. Fe₂O₃). Glass is an inorganic material that is stable, resistant to most chemicals, has a very high hardness (600-800Kp/mm) and very high tensile strength of 10⁴ N/mm². The high silica dioxide content causes glass to be extremely brittle so that glass fails under stress by shattering into pieces, reducing its structural qualities drastically through imperfections in the glass material.

Optical Characteristics of Glass

For the building skin glass is of particular interest for its optical properties. Glass transmits up to ninety-five percent of radiation in the wavelength range of 200 to 3000nm while being almost opaque to the far infrared radiation beyond 3000nm. This characteristic allows glass to be used to trap solar radiation with its main energy content in the ultraviolet, visible and near-infrared spectrum (energy content of solar radiation: 3% UV, 53% VIS, 44% NIR). Thus glass transmits solar energy into a building while blocking the far-infrared radiation of warm inside surfaces to the outside. This principle has led to the development of glass conservatories and the use of glass for solar heating in various systems. Unfortunately this characteristic is also the cause for the high cooling loads in buildings with extensive glass surfaces that are not properly shaded, as can be seen in most modern office buildings. To reduce these high cooling loads reflective or body tinted glasses with lower transmittance have been developed.
%reflectance = 100\%) as well as the distribution of these values in the
wavelength spectrum (simplified as visible and hemispherical values or as a
detailed values for the complete radiant spectrum). These values depend on the
incident angle under which radiation hits the surface and whether it is direct or
diffuse light.

For the design process the critical parameters are visible transmission ($\tau_{\text{vis}}$) solar
transmission ($\tau_{\text{sol}}$) and the total solar energy transmission, or g-factor. The g-
factor takes into account the primary radiant heat gain as well as the secondary
heat transfer from the glass into the room caused by convection, conduction and
radiation.

Thermal Characteristics of Glass

The high density of glass causes its poor thermal performance as an insulator
and its high thermal conductivity. Normal float glass has a thermal conductivity of
1 W/mK (compared to wood, 0.15 W/mK, concrete, 0.93 W/mK, or brick 0.7 W/
mK). For this reason single pane glazing is usually no longer used for the
enclosure of inhabited spaces in most climates. Assemblies of two or three layers
of glass filled with low conductivity gasses improve the thermal performance of
glass and are now standard in most construction. Even with highly sophisticated
assemblies the U-Value of windows is lower than the values that can be
achieved with other wall constructions. In order to determine the optimal
configuration and sizes of windows an energy balance must be established,
taking into account the energy gains from solar radiation and the energy losses
through the window.
3.1.2. State of the Art

With the availability of a large volume production process and improved control in glass manufacturing the manipulation and application of glass has been greatly increased in the last thirty years. An increased interest in the use of glass and experimentation with new products emerged in contemporary architecture and a vast range of products is currently available to designers. These technologies have been documented extensively in recent years and the scope of this thesis is not broad enough to discuss all available options. The following section discusses a selection of the three principle technologies of manipulating glass relevant to innovations proposed in this thesis.

Manipulation of the Base Material

The process of manipulating the ingredients of the glass mold and the production of float glass allows the manufacturing of large panes of glass and a tuning of the transmittance of glass through its base material. The limitation in sizes available in glass panes are primarily the width of the float plant for the production, the thermal expansion in large panes and the handling of such large fragile elements during transport, and construction. Glass panes for single pane glazing can be up to 3 m by 8 m while insulated glass with its different thermal expansion in the two glass panes usually prevents sizes bigger then 2,6 m by 4,5 m. However, in special cases even bigger sizes can be manufactured.

By changing the base material body tinted or clear-white glass can be produced and is frequently used today especially in the design of multi-layered building envelopes. The use of clear-white glass allows for even higher transmission of solar energy into the building than the typical float glass with its slight greenish tint. Through this process the color of the glass and thus the color of the light that
is transmitted can be manipulated. In addition a selective transmission of wavelength ranges can be achieved. Even if not yet used in building construction, glass with photo- or thermo-sensitive additives can be produced that change the transmittance of the glass based on the temperature or exposure to radiation. This technology is frequently used for optical glasses and attempts have been made to introduce this technology into buildings.

Manipulation of the Glass Surface

In the manipulation of the surface of glass, technologies are now available that manipulate the strength of glass as well as its transmittance. In the process of cooling and re-heating the glass in its production, glass can be pre-stressed to increase its tensile strength. This increase in structural performance led to the development of structural facade systems that support their own weight. These systems have led to an even further dematerialization of the building envelope and are currently used in many large scale buildings. Facades of up to 25 m height can be created by connecting suspended panes of glass. The structural support for these systems is usually reduced to tensile systems to support the facade against wind loads. But even on smaller scales this treatment of glass can be used to achieve structural elements made of glass or to reduce the risk of injury by creating glass that fractures into small pieces if it fails, a technology used in the production of car windows.

Treating the surface of glass with coatings or chemicals can alter the appearance or transmission properties. The process of coating glass with thin layers of metal alloy film is of special interest in the context of the energy balance of a construction. The current standard of low-emesivity coatings reduces the radiant heat loss through a window by reducing the emissivity of the glass surface. Other
coatings can be created to reflect most of the near infrared radiation of the sun thus reducing the energy transfer into a building. The nature of these coatings allows for selective and directional filtering of wavelengths with or without visible effects. Especially in the layering of multiple panes of glass these coatings can increase the thermal performance of the assembly significantly by manipulating the radiant heat transfer.

Manipulation of the Assembly

The ongoing search for windows with better thermal performance through the creation of multiple glass pane assemblies led to the development of windows with high thermal resistance, k-values. The new developments of windows attempt to achieve thermal resistance, as represented by the k-value, that approaches the performance of conventional wall constructions. Combining layers of coatings and gaseous fillings, the heat loss through conduction and radiation is reduced and as an effect the inside surface temperatures are raised and thus the indoor comfort is increased. The performance of windows reaches in some instances a point where the heat loss through the frame is higher than through the glazed area and current research seeks to achieve better overall k-values for windows by improving the frames of assemblies. Also, the acoustical performance of these assemblies has been improved and multiple pane assemblies are used on the exterior and interior to reduce sound transmission through glass.

Through the lamination of glass new qualities have been added and specialized glasses are available for fire or impact protection. In the search for glass elements that are able to adjust to changing conditions, technology is now available to laminate films with varying properties between glass panes. This
technology includes the use of Liquid-Crystal-Films that can change from transparent to translucent by applying an electric field. These glasses are primarily used for privacy applications since their high radiant energy transmission even in the translucent state prevents them from being used for the control of solar energy gain. Similar films are available that react to illumination or thermal changes to initiate changes in the transparency. These materials are a first step towards the creation of walls that adjust to changing climate conditions based on a transformation of a single element instead of mechanical devices like blinds or louvers.

3.1.3. Future Developments

To develop window construction with even better thermal performance, current research investigates a multitude of aspects, from better sealant, spacers, gas fillings and improved coatings to elements that redirect light for better natural indoor illumination. This thesis focuses on the development of materials and assemblies that allow for an active control of solar energy gain based on a change in the radiant energy transmittance. Three developing technologies are discussed briefly in the following section.

Gasochromic Systems

Gasochromic systems are a relatively new variation in the work with electrochromic materials. Electrochromic substances are defined through their change in radiant transmission based on the addition or subtraction of free electrons in their atomic structure. This phenomena can be found in a range of materials like Wolfram, Titanium, Iridium and Tungsten. The use of these materials is discussed in the following section.

5 see Marko, page 52
materials as coatings on glass has been investigated extensively in the last three decades. In gasochromic systems, a layer of wolfram-oxide is coated on the inside surface of a glass pane in a double pane glass assembly. Flushing the space between the panes with a gas mixture with additional hydrogen ions are added to the wolfram-oxide causes this layer turn gradually to blue opaque. This process can be reversed by flushing it again with a gas mixture with added oxygen which causes the hydrogen-ions to leave the wolfram-oxide and a bleaching of the layer is achieved. The advantage of this system is that in comparison to other electrochromic systems no multiple layers of coating are needed. With this system values for $\tau_{\text{sol}} = 74 - 14\%$ transmissivity have been achieved in prototype windows, values higher than in other electrochromic devices.

The advantage of this better performance and simpler coating technique must be evaluated against the higher installation requirements in order to supply the gas mixtures to the glass panes. Studies on this technology are currently carried out in Europe at the Institute for Solar Energy Systems at the Fraunhofer Institute in Germany. It is an interesting example of a technology by which substances, in this case gas, are supplied to a glazing unit in order to change its characteristics. Another example of such an approach is the idea of circulating water through the cavity of double-paned glazing, an idea that was explored in England in the late 1980's but hasn't yet made any serious progress.

**Suspended Particle Displays**

E.H. Land, inventor of Polaroid polarizing materials and instant photography, discovered the core idea of Suspended Particle Displays (SPD) in 1934. At this time Land was searching for a material that could polarize light to be utilized in

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**Image 26:** Technical concept of gasochromic system. Gas flows in between to panes of float glass and over one layer of electrochromic coating.
the film industry. The technical concept is that colloidal particles suspended in a film or liquid are randomly aligned and due to their random configuration reduce or totally block light from passing. When these particles are exposed to an electric field they align and allow light to pass through. Numerous companies have worked on the technology since, but so far without any breakthrough results.

The configuration usually chosen for this technology is to place a thin film of suspended particles between two pieces of glass that are coated with an electrically conductive transparent material. The particles are dispersed in their liquid carrier by coating them with a polymer that dissolves in the liquid. By varying an applied voltage, more and more of the particles align and the user can rapidly and continuously control the amount of transmitted light through the material. Since the material changes gradually from transparent to black opaque it has a high potential to be used to control solar heat gain and to adjust levels of indoor illuminance. A disadvantage of this system is the need for a continuous input of electric energy to keep the film in a state other than opaque, making its use from an energy-saving standpoint questionable. Also, issues of large scale production, durability and panel sizes are yet unresolved. However, with the improvement of thin film technology this material may be soon applicable for the construction industry. Companies like Research Frontiers, N.Y., are actively developing the technology for buildings.

The advantages of this concept are very short switching times and the potential to create wavelength selective transmission though the introduction of different particles. Also the fact that the system can be controlled by an electric field provides the opportunity to regulate the windows easily via a central building control system or the individual user.

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6 see for example the work of Research Frontiers Inc., Woodbury, NY.
Electrochromic Glazing

Electrochromic glazing is based on the above mentioned phenomena of a change in radiant transmittance based on the addition or subtraction of electrons in various substances. In general terms electrochromic glazing is understood as the combination of multiple coatings of film that allow for a reversible exchange of electrons through the application of an electric current. The most widely used configuration consists of a layer of tungsten oxide, $\text{WO}_3$ as an electrode, and lithium nickel oxide $(\text{Li}_{0.5}\text{Ni}_{0.5})$, as a counter-electrode, separated by polyethylene oxide (PEO) as an ion conductor. Via a transparent conductor material a current is applied to these layers and ions move from electrode to counter-electrode or vice-versa, causing a change in the transmissivity of the tungsten oxide. A big advantage of this system is that electricity needs to be supplied just for the ion transport not for the upkeep of a certain state. Therefore this system is very interesting from an energy standpoint since its consumption of electricity is by far lower than in Suspended Particle or Liquid Crystal systems.

The complete bleaching and coloring of such a glazing unit requires an electric current of $10\text{mA}$ at $3\text{V}$ for the time of $250$ to $400$ seconds. A change in transmittancy from $\tau_{\text{vis}}$ of $75\%$ to $2.5\%$ and $\tau_{\text{sol}}$ of $59\%$ to $1.6\%$ can be achieved. The lower values for $\tau_{\text{sol}}$ are caused by a high reflectance of the NIR spectrum in the bleached as well as in the colored state. These values can be varied through changes in the thickness and composition of the facilitated layers. Also the color of the system can be manipulated through changes in the electrode or counter-electrode materials. Usually the layers are laminated between two panes of float glass, similar to the lamination of other glasses. This enclosure protects the layers from environmental impact and degradation.

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7 see Rottkay, Optical Modeling of a Complete Electrochromic Device
8 values provided by Pilkington Ltd.
Longevity studies in research facilities have shown no change in the material nor in its switching properties over more than five-thousand cycles\(^9\) making it comparable to the longevity of other glazing products with advanced coatings.

These characteristics of electrochromic glazing have made this technology one of the most likely candidates for the introduction to "smart windows", a term for new adjustable window technology. Large research projects, funded by the U.S. Department of Energy and the European Union, support these projects. The potential of these systems to significantly reduce cooling loads, especially in the retrofit of commercial buildings with extensive glass facades, was one of the biggest incentives for these projects. The main obstacles in the development of commercial products was the problem of applying these layers correctly and issues of scale for the production of larger elements. By now most of these problems seemed to be solved and Pilkington is the first firm that markets an electrochromic glass with sizes up to 2.6 by 1.2 m\(^10\). The anticipated price of these systems has been estimated by some companies at 100-250 US$ per square meter.

Part of the exploration of the potential of electrochromic glazing in recent years has been the simulation of these windows in terms of their energy and visual performance. The Lawrence Berkeley National Laboratories have executed a number of projects showing the advantages of this technology for the control of indoor lighting levels for workplaces and the reduction of energy required for cooling and lighting in residential as well as in commercial projects\(^11\). As a result of these efforts, initial attempts have been made to develop simulation

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9 see Rubin
10 data supplied by Pilkington Ltd.
11 see Sullivan et al. and Moeck et al.
parameters and software for the energy simulation with the widely used TRANSYS and DOE2 as well as for lighting simulation with RADIANCE.

Electrochromic glazing is at this time the most feasible technology to be used in "smart windows". It will change the requirements for heating, cooling and lighting and will thus have a significant impact on the layout of building systems. Moreover, it will be the first and most available material for the building industry with changing material properties and it is anticipated that it will trigger an important change in the perception of the properties of buildings.

3.2. Insulation

Insulation materials play a crucial role in the search for a better thermal performance of the building envelope. The quest to develop better assemblies or components has led to new concepts and solutions in recent years. The adoption of these technologies has the biggest potential to significantly reduce the energy consumption of buildings, especially in cold regions or building types where heating systems are dominant.

3.2.1. Summary

Traditionally, most building envelopes were designed as load bearing, monolithic structures with small openings for access, ventilation and illumination. The choice of material was strongly determined by the locally available building materials, local climate conditions and manufacturing technologies. Materials commonly used were stone, masonry, adobe and timber. The overall thickness of the wall was the primary means to manipulate heat loss through the wall and orientation
and configuration of the building and openings were carefully chosen to maximize the thermal comfort on the inside. In colder regions due to the high heat loss of most of these structures the location of internal heat sources, usually some sort of fireplace, was of great importance and buildings had high indoor temperature changes. The use of massive walls reduced these temperature swings and indigenous examples of such constructions can be found predominantly in locations with high diurnal temperature variations.

Exceptions from this general overview are for example the temporary tent structures of nomadic populations and some instances in which composite materials for the wall assembly were created. Examples for these types of composites are the half-timber constructions of Europe with their adobe straw in-fills into timber frame construction or the use of lightweight ingredients in the mixture of concrete.

With the development of advanced control systems for heating and cooling during the last two hundred years people adjusted to smaller temperature changes on the interior. This is a significant change from the historical situation of adjusting clothing, activity and the use of space with changes in the inside temperature. Today we assume an almost fixed indoor temperature as the desirable condition. This change in our expectation of indoor comfort requires the use of large amounts of energy to heat or cool to this predefined temperature range. This development generated the development and search for materials with a low conductivity like glass or mineral fiber and the improvement of traditional building materials like brick to achieve lower values for the thermal conductivity. This development is still ongoing and has increased intensity in recent years with tighter codes and building regulations for the thermal performance for buildings. Today specific values for maximum heat loss through the building envelope are regulated by governmental authority and proof of this

Image 29: Swiss farmers building as example for indigenous architecture in response to severe weather conditions. Thick stone walls with small openings serve as protective layer against the environment.
performance is part of the application process for building permit in many industrialized nations\textsuperscript{12}.

The key parameters are the thermal conductivity of a specific material, \( \lambda \) in W/mK, the thermal transmittance, \( U \) or \( k \) in W/m2K, and thermal resistance, \( R \) in m2K/W, of the overall assembly. Important is also information regarding the permeability to air, vapor and water. In the design of wall sections the determination of the temperature gradient throughout the assembly is relevant to avoid moisture damage based on condensation within the construction. The issue of water or moisture becomes very important in this respect also for another reason. Water with its high thermal conductivity reduces the thermal properties of most insulation if it is absorbed. The open porous structure of most well insulating materials can absorb moisture easily and requires the careful detailing of moisture and vapor barriers.

3.2.2. State of the Art

Construction methods for walls in residential buildings vary significantly in Europe and the United States. In Europe the predominant construction methods are load bearing brick or concrete walls with an added layer of insulation on the outside to decrease the thermal transmittance. This layer of insulation is usually some form of rigid polystyrene boards or polystyrene particles in an applied plaster. In the United States most construction is a standard wood or metal stud framing construction with bat insulation and some form of inside and outside sheathing. This construction method has a much lower thermal mass than the European system and is constructed with less construction equipment and shorter construction time. On the other hand the European heavy construction is usually

\textsuperscript{12} see as an example the German Waermeschutzverordnung
designed for a longer life span and allows for the use of heavier floors and interior walls, increasing the overall acoustic properties and fire ratings. The fact that the American system is mainly based on a wood construction with its better ecological and economical performance has led to an increased interest in this construction technique in Europe. Both systems allow for a high flexibility in design and performance and other products like windows and doors have adjusted to these systems in terms of module sizes and connections.

With the introduction of more insulation and a tighter construction to prevent infiltration both of these wall systems have decreased the ability to transfer moisture through the wall. This has led in recent years to more cases in which fungus or mildew started to become serious problems in new constructions due to high humidity content indoors. To avoid these problems and its damaging implications for inhabitants and construction more and more new residential construction uses mechanical devices to increase the air and humidity exchange with the exterior. These devices are now available as decentralized systems with integrated heat recovery units to reduce the heat loss through ventilation. A trend towards highly insulated, airtight envelopes with mechanical space conditioning systems can be observed even in residential construction. If installed and operated properly these systems allow for significant energy savings.

With growing concern for the environment researchers have in recent years started to compile information on the environmental impact of construction materials and technologies. Especially for the building envelope studies explored the relationship of increased investment, in terms of money and energy, to more insulation to the energy savings for the operation of buildings. These assessments also include the comparison of the CO₂ emission during production,
operation and recycling of the construction materials is used as well as other environmental and health concerns.  

The most interesting new products on the market today for insulation purposes in combination with monolithic walls are translucent insulation materials, short TIM. These products, made of clear acrylic or glass, create small transparent or translucent cavities to trap air and create a thermal barrier while still allowing solar radiation to pass. This arrangement allows for the use of solar energy to heat up the thermal mass of a wall during the day and reduces the heat loss of this wall at night. Even so, these insulation materials have generally lower insulation properties than other products their energy gain during the day makes them actually better in the overall energy balance if compared to other opaque materials. The differences in material, orientation of the cavities, depth and gas fillings are primary parameters for the performance. These systems can be used adhered to the wall and then covered with a glass pane or a new type of translucent plaster. Also through the trapping of air or gas in these systems the k-value of double-pane glazing can be reduced. In conventional double-pane glazing, if the spacing of the glass become too big a convective heat flow starts. By introducing TIM's, the convective flow is blocked even for spacing of glass panes of 0.10 to 0.15 m creating a k-value of 2.2 W/Km for the overall system. These systems can be used for high performance Trombe wall as well as for translucent well-insulated glass elements. In addition to the thermal benefits they create, TIM's also add an interesting visual quality to the wall assembly by providing a layer of translucency over the wall surface.

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13 see Steiger
14 see product StoThermSolar produced by STO Germany

Advanced Building Skins - S.M. Building Technology - N. Kienzl - School of Architecture - MIT '99 52
3.2.3. Future developments

Since the energy for heating buildings is a major source of the energy consumption for the building operation in most climates, researchers and corporations are currently working to improve insulation materials and concepts. One approach is to use existing materials and technology and increase the amount of material used. This way extremely high insulation values can be achieved and the use of this super-insulation has been highly promoted by some researchers in recent years. However, some new aspect have emerged in this field that are of interest in the context of this thesis and are discussed.

Regenerative Insulation Materials

Most of the insulation materials currently in use are either oil derivatives or use extensive energy in their production. The search for building materials with low embodied energy content has led to the exploration of sustainable products. Also, the heightened concerns for indoor air quality and indoor pollutants affected by the use of building materials has spurred research in the use of natural materials, especially for residential construction. These concerns have led to research in the field of regenerative insulation materials. Organic substances like paper, wood, wool, cork and reed have been studied for their use as insulation materials. The benefit of these materials lies in their low or even positive impact on the environment as well as in the belief that natural materials provide a healthier indoor climate. The biggest problem in the use of these organic materials is their longevity especially if in contact with water, their fire rating and their thermal performance. Progress in these areas is possible and the potential of growing fields of energy saving insulation makes it an interesting alternative to conventional technology. Unfortunately the scientific exploration of these
materials is often overshadowed by polemics from different ends of the environmental spectrum. The promoters of natural materials tend to praise qualities of this insulation disregarding issues like durability and chemicals used to improve the fire rating, while the promoters of conventional technology disregard this technology as inefficient. A serious discussion and research on the pros and cons of these materials and all their implications need to be explored.

Gas Filled Panels

The use of inert gases for installation purposes has been explored extensively in the past for use in double pane glass windows due to their low thermal conductivity. Just recently research started to use these gases as filling for lightweight panels for the building industry\textsuperscript{15}. Here low conductivity gases like argon or krypton are used at atmospheric pressure within multi-layered infrared reflective baffles. These self-supporting, flexible panels can be made in various shapes and could be used as replacement for bat insulation in framing construction. Performance tests on 25mm thick prototype elements have shown apparent thermal conductivity values of 0.028 W/mK for air filled panels, 0.020 W/mK for argon filled panels and 0.012 for krypton filled panels (compared to expanded polystyrene with 0.029 W/mK). The baffle construction consists of multiple layers of thin film with aluminum coating in a honeycomb like section. The coating reduces the radiant heat transfer while the honeycomb structure stabilizes the panel and traps the gas thus minimizing convective heat transfer.

These materials and technologies involved for the production of these elements are readily available and a final market price of 8 to 15 US$/m\textsuperscript{2} can be

\textsuperscript{15} see Griffith
The next step now is to determine how these panels could be integrated into conventional construction. Since the panels have to be sealed off-site and can not be cut or even punctured during construction there are some major process issues that need to be explored. It seems most likely that the use of these panels would make most sense in prefabricated elements or very standardized construction. However the excellent performance, low material needs and relatively low cost could make this an interesting option soon.

**Aerogel**

Its special material properties make Aerogel is the most effective thermal insulation known. It belongs to the group of translucent insulation materials discussed earlier in this text. These properties have made Aerogel extremely interesting for a wide variety of applications from thermal insulation to x-ray lasers. The development of Aerogel technology is currently under way at various locations around the world and even in space missions, in which NASA explores the production of Aerogel under zero gravity. Special attention has been given to its potential as super insulation for windows or other building applications and it is the most advanced and promising technology in the field of thermal insulation.

**History of Development**

Aerogels are a class of low density solid foam materials that are characterized by having open cell structures composed of particles usually smaller than 10nm in diameter with pore sizes usually smaller than 50nm in diameter. They were initially developed 1931 by Steven S. Kistler of the College of the Pacific in

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16 see Griffith, page 9
17 see Smith for detailed discussion of potential applications

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Advanced Building Skins - S.M. Building Technology - N. KienzI - School of Architecture - MIT '99
Stockton, California\textsuperscript{18}. His intention was to create a "dry" gel that contained a continuous network of the same size and shape as a wet gel. In these experiments, Kistler prepared silica gels in an aqueous environment using sodium silicate. The transformation of these wet gels to solid foam required the exchange of the water in the gel with alcohol and then the drying of the gel by converting the alcohol to a supercritical fluid and allowing it to escape. Thus, a transparent, low density and highly porous material was created. Kistler continued his exploration of Aerogel for many years by studying its behavior and the potential of other inorganic and organic materials to be converted to Aerogel.

In the late 1930's Kistler joined the Monsanto Corporation and a commercial Aerogel was produced under the tradename Santocel\textsuperscript{19}. This product was a granular silica material and was used in cosmetic products until the 1960's when it was replaced by cheaper fumed silica. Largely forgotten, Aerogel regained the attention of the scientific community in the late 1970's when its potential for the aerospace industry was discovered. Researchers set out to simplify the production process of Aerogel and by utilizing tetramethyorthosilicate (TMOS). A solution of methanol produced an Aerogel in one step which reduced the production time significantly. In the early 1980's this process was further simplified by replacing TMOS with the less toxic tetraethylortosilicate (TOES) and replacing the methanol with liquid CO$_2$ without reducing the quality of the Aerogel. At the same time experiments with the creation of Aerogel from other materials were conducted.

A second attempt was made in the early eighties to commercialize Aerogel and it is currently produced by a small number of firms world wide in small quantities mainly for research purposes. The primary focus of this production is to create

\textsuperscript{18} see Hunt, A Brief History of Silica Aerogels
\textsuperscript{19} as reported by Smith et al.
monolithic plates of silica Aerogel for the use in advanced instruments, like Cerenkov detectors, and for aerospace applications. Parallel to this development researchers and designers became interested in the use of Aerogel in the construction industry because of their optical and exceptional thermal properties.

Optical Properties

The optical properties of monolithic Aerogel can be described as transparent. Its solar transmittance can achieve $\tau_{\text{sol}} = 85\%$ for a pane of 20mm thickness and if produced with pore sizes of around 50nm it appears to be transparent in the visible wavelength range. Through Raleigh scattering on its internal surfaces it shows a bluish haze when looked at against a dark background and tends to produce a reddish haze for transmitted light. Critical for the reduction of this haze is the production of a very uniform pore size and experiments carried out by NASA explored the effect of zero gravity during the production of Aerogel on the uniformity of the pore sizes. The potential production of such uniform Aerogel fuels the discussion of Aerogel as an in-fill material for double pane glazing units in the future.

More readily available and cheaper to produce than monolithic Aerogel are granular Aerogels. Granular Aerogel can be produced through pulverization of monolithic pieces or through emulsion polymerization. Granular sizes up to 10mm in diameter seem feasible to produce and the characteristics of different granular sizes have been studied and compared. The solar transmissivity of granular Aerogel is lower than of monolithic material and is very dependent on

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20 see LBNL websites on Aerogel activities, http://eande.lbl.gov/Aerogels/satoc.htm
21 see Schmidt, Beck and Smith
the granular size. Smaller granular sizes have a lower transmissivity of around \( \tau_{\text{sol}} = 10\text{-}20\% \) for 0.5-2mm granules while values of \( \tau_{\text{sol}} = 50\text{-}60\% \) can be achieved for 3-5mm granules. Even higher values, comparable to the values of monolithic material has been reported to be achievable\(^{22}\). Granular Aerogel diffuses light very evenly, has a white color and it exhibits the same scattering effect as monolithic Aerogel.

**Thermal Properties**

The unique pore structure of Aerogel reduces all three modes of heat transfer to a minimum. Conduction is prevented through the encapsulation of air or gas in the microscopic pores. Conduction through the material is minimal due to the low percentage of substance per volume (between 1 and 10\%\(^{23}\)) and its loose network. Since the mean free path in air for far infrared radiation is around the same or longer then the pore size of Aerogel photons collide with the Aerogel and radiation is blocked. This effect can even be increased by changing the mean free pass of light by applying a light vacuum of one bar load to the Aerogel. This results in a very low thermal conductivity of 0.013 to 0.017 W/mK or \( ~ R-10/\text{inch} \) for monolithic material.

For granular material the values are higher and depend again on the sizes of the granules since here heat transfer between the granules can occur. A relationship between size and conductivity can be established in which larger granular size results in higher conductivity due to bigger gaps between individual granules\(^{24}\). For granular sizes of 0.5 to 2mm a conductivity of \( \lambda \sim 0.02 \) W/mK has been achieved.

\(^{22}\) see Beck


\(^{24}\) see Smith
determined\textsuperscript{25}. This value can be reduced by packing the Aerogel granules very
dens by applying again a vacuum of approximately one bar load. In this
configuration granular Aerogel can reach values for thermal conductivity similar
to monolithic material\textsuperscript{26}.

Acoustical Properties

Another interesting aspect of granular Aerogel is its ability to absorb sound.
Studies have shown that a layer of 40mm Aerogel granules with sizes in the
range of 0.5 to 2 mm have a coefficient of absorption of 65% in the frequency
range of 650KHz to 1KHz\textsuperscript{27}. This ability might not only improve the acoustic
qualities of glazing units but also opens up the potential use of Aerogel for footfall
insulation in floor constructions or other acoustic applications.

Technology and Cost of Production

The biggest obstacle on the way to commercialization of Aerogel are the high
production cost and the uncertainty of its market acceptance which prevents
companies from investing in large scale production facilities. In the analysis of
the cost in the production of Aerogel the cost for the base material is the biggest
factor. Studies showed that with industrial production and efficient equipment use
the cost of Aerogel can be reduced to values comparable to fiberglass for the
same area and insulation value\textsuperscript{28}. A development that would enable the
production of Aerogel from a cheaper base material would have a significant

\textsuperscript{25} information provided by Cabot Corp.
\textsuperscript{26} see Schmidt
\textsuperscript{27} see Schmidt
\textsuperscript{28} see Carlson
impact on the overall cost and would clearly help its introduction into the
construction market. Also the use of industrial scale machinery and a constant
production would reduce the energy consumption per unit and thus make
Aerogel even more feasible from an energy standpoint.

Outlook
Aerogel is certainly the most interesting new insulation material because of its
outstanding material properties and its potential for applications in solar
architecture. Due to the extensive research of recent years and the involvement
of major corporations and research institutions it seems likely that this material
will soon be commercially available. The biggest questions at the moment seem
to be what are the characteristics that are the most applicable in the design of the
Aerogel (granular sizes) and how to make the best use of it. Especially the
successful application needs to be developed now in terms of the detailing and
integration of Aerogel components. Also the use of Aerogel opens up a wide
possibility for designers to start experimenting with this innovative material and
this thesis presents one approach of how such integration could be achieved.

3.3. Energy Storage
The storage of thermal energy gained from an exchange with the environment
can be used to reduce the auxiliary energy consumption for heating and cooling.
It therefore should be an integral part of all attempts to reduce the operating
energy of buildings. This principle aspect has been discussed earlier in this text
and the following section focuses solely on the materials and systems facilitated
for this purpose. Especially since this aspect of energy storage is currently seldom fully utilized and traditional methods are no longer applicable to modern construction techniques, the exploration of new concepts and materials is particularly relevant.

3.3.1. Summary

Traditional thermal energy storage was tightly connected to the choice of building material and construction method. Building materials with a high thermal mass like brick, stone or adobe were utilized to dampen diurnal temperature swings. The higher the day and night temperature difference was the more massive these constructions were carried out. Prominent examples of this use of thermal mass are the pueblo constructions in New Mexico with their thick adobe walls. A vernacular understanding of how to use the available building materials in the specific climatic context was part of building traditions and influenced not only construction methods but often also the sizing of elements accordingly.

In climates with low diurnal temperature changes but with large seasonal changes other storage methods were more applicable and in many cases the ground was used as the biggest available thermal mass. Here the slow reaction and almost constant temperature of the earth led to the use of building forms that were partially or fully buried in the ground. Also the use of water with its large thermal storage capacity was used to dampen temperature swings either by including elements of water within the building or simply by locating buildings close to larger bodies of water.

The advantage of the use of thermal storage in the envelope is the increased surface temperature of these elements. Since in such a construction the interior surfaces are mostly at the same temperature as the ambient temperature a very
Thermal Diffusivity $\alpha$ [mm$^2$/s]:

$$\alpha = \frac{k}{\rho \cdot c_p}$$

$k$ = thermal conductivity [W/m*K]  
$\rho$ = density [kg/m$^3$]  
$c_p$ = specific heat [kJ/(kg*K)]

Typical values for $\alpha$:
Concrete: 0.7 to 1.4  
Steel: 1.0  
Wood: 0.14 to 0.17  
Insulation: 5.6 to 0.7  
(from ASHREA fundamentals)

even temperature of all surfaces and thus a high thermal comfort can be achieved.

The use of thermal mass has to be considered carefully since a high thermal storage capacity means also a slow thermal reaction to changes. This means that in structures that are just used for very short periods or in which internal temperature changes are desired, the use of thermal mass would have a negative impact on the performance. Here a much higher energy would be needed to allow for quick changes and a light weight construction might be more sensible for such constructions.

With the introduction of building materials with a higher structural performance like concrete and steel the use of monolithic heavy building materials diminished and thus did the thermal storage capacity of buildings. The American use of wood framing construction techniques had the same effect for residential structures and the increased use of insulation materials in these light weight constructions decreased the heat loss but did not provide any damping of temperature swings.

The key parameters are the thermal storage capacity and the thermal diffusivity of the building material used. Thermal storage capacity is defined as the product of the material's density, specific heat and conductivity and determines the amount of energy that can be stored within a given volume of material. The thermal diffusivity is defined as the conductivity divided by the product of density and specific heat and determines the speed by which heat travels through a material and thus how fast a material reacts to temperature changes.
3.3.2. State of the Art

The construction type chosen still primarily influences the current use of thermal storage. In Europe the use of reinforced concrete and brick still provides a certain level of thermal storage within the construction and recent attempts to increase this effect led to the thickening of floor slabs and other structural elements. These systems are often coupled with low temperature water systems to create chilled ceilings or floor heating. This combination reduces the energy consumption and this effect can be even increased by the use of other energy-efficient systems to produce the low thermal energy for heating and cooling. Also the before mentioned use of translucent insulation materials in combination with thermal mass in the building envelope led to a heightened recognition of thermal storage.

In the United States with its predominant use of steel in commercial and wood framing in residential construction the use of thermal storage strategies is minimal. In the seventies some attempts were made to use solar energy in combination with thermal storage strategies. These strategies often tried to facilitate materials with a high thermal storage capacity and the use of water walls, Trombe walls and similar systems was the result. Due to the big weight of such systems, cost and practical reasons, these systems were not widely accepted and are still just used on rare occasions\(^\text{29}\).

In recent years the concept of storing thermal energy generated during peak times remotely in the ground, in rock beds, for the generation of ice or in other mediums led to the development of systems currently used in some commercial and residential buildings. These systems often use the heat stored in the summer months to reduce the overall energy needed for heating during colder seasons and are actively developed by some engineering firms\(^\text{30}\). The big advantage of

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\(^{29}\) for a discussion see Moore

\(^{30}\) see Daniels for a discussion of some of these concepts
such technologies is that they can be efficiently combined with other HVAC systems and seldom require special construction within the building. Their concentration of heat storage in one location or facility makes these systems technical and economically more feasible.

Another aspect of energy storage is the use of active solar technology. Here not the storage of low temperature heat for heating purposes but for high temperature heat or even electricity is explored. The predominant use of high temperature heat is for the generation of hot domestic water. The storage of this high energy content in well insulated storage tanks is relatively easy and cost effective. The technical developments in the field of photo-voltaic technology provide increasing efficiency in the conversion of solar energy into electricity. The economic value of electricity prevents these systems from being used for heating and cooling purposes and they are better used for other applications. These systems are mentioned here since they also provide means to store energy and their integration into the building envelope opens interesting new possibilities.

3.3.3. Future Developments

Phase Change Materials

The process of storing energy in a material can occur in three ways. First the increase in Brownian motion of the materials molecules represents our conventional understanding of heating up a substance. Energy stored in a substance this way is referred to as sensible heat. It is defined by the specific heat of a substance $c_p$ [J/(kg*K)]. The second way is the energy storage in a phase change. If the Brownian motion within a substance reaches a critical point, the bonding between the molecules cannot maintain its structure anymore and the material changes its bonding structure or its phase, as seen in the changes
from solid to liquid, liquid to gaseous or solid to gaseous. This phase change occurs at a specific temperature and pressure and is reversible. During the transition of one phase to another, all energy absorbed is used for this purpose and no increase in sensible heat or temperature occurs. The energy required or released during such a phase change is referred to as latent heat. It is a material property and described as enthalpy of fusion or enthalpy of vaporization [kJ/kg] depending on the phase transition that occurs. The third process of storing energy in a material is the energy absorbed or released during a reconfiguration of different materials referred to as thermochemical storage. This energy storage can be observed in many exo- or endo-therm reactions in which the combination or separation of various substances releases or absorbs heat. This process is dependent on the materials involved and not always a reversible process.

Latent heat storage is unique because during the phase change a comparatively high amount of energy is absorbed without an actual increase in temperature. For example, water, a material with a very high specific heat, requires for its phase change 333 kJ/kg compared to the 4 kJ/kg required to increase the temperature of water by 1°C. This means that, while increasing its sensible surface temperature from 0°C to 1°C and thus changing its phase from solid to liquid, stores eighty times more energy than the same volume of water that is heated from for example from 10°C to 11°C. This potential to store large amounts of energy in a small volume has been explored as a way to store thermal energy for buildings since around 1930.

The use of phase change materials (PCM), especially the phase change for vaporization has been explored in many applications and is used today frequently in various forms of technical equipment. The large change in volume

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31 data from ASHREA Fundamentals
32 for a discussion of the history of phase change materials see Lane

Advanced Building Skins - S.M. Building Technology - N. Kienzl - School of Architecture - MIT '99
during vaporization is the effect that is used in most of these applications. For use in buildings the change from solid to liquid is more applicable because of its lower temperature range and the smaller change in volume that occurs during fusion. Especially the lower temperature for fusion for many materials made this type of phase change very interesting for the storage of thermal energy for the heating and cooling of buildings as well as for other applications related to the human body, like medical equipment or clothing.

This interest spurred a whole series of research efforts to determine the materials best suitable for such uses as well as their performance and long-term stability. Another advantage for phase change materials for space heating purposes is that their melting point can be ideally just above room temperature. Since so much energy is stored at that point no higher energy level is needed and also no higher surface temperature desirable if the phase change material is directly exposed to the interior. This low temperature required for charging the PCM made it a very suitable material for the use in solar applications. Research in these types of phase change materials was therefore often connected to an increased interest in solar applications during times of energy shortages. For example, in 1948 an experimental system was designed by Dr. Maira Telkes, a researcher at MIT, for a house in Dover Massachusetts. In this project a Glauber salt hydrate based PCM was used in combination with south facing solar collectors to supply all the heat required for the 135 m² residential building. Telkes became one of the leading figures in the research of PCM materials, in particular in the work with salt hydrates, and improved the performance of these substances over the years.

In the sixties the research on PCM shifted slightly to high-end applications in aerospace programs and just after the oil crisis in the seventies a strong support
for research in this field became publicly available again. During the research in this time many materials where investigated and data on their performance collected. The biggest problem in the use of these materials was and still is their long-term stability. Especially the highly efficient hydrate-based materials tend to separate after repeated freezing and thawing cycles and diminish drastically in their storage capacity. Thus research was conducted to either repeatedly mix the PCM material to keep its integrity or to add agents to prevent the separation. Partial success has been reported in these strategies and especially the storage of PCM in gels has been successful. In general, the smaller the volume in which the PCM is contained, the longer it will stay stable and keep its performance. In the use of gels, hydrate-based PCM’s are submerged in a polymer structure that prevents separation of the PCM and provides structural stability even if the PCM liquefies. Other approaches to this problem is the encapsulation of PCM in small pellets or within other material.

Glauber salt or Calcium Chloride, CaCl₂, was used as a base material during many of these studies with hydrate PCM due to its high enthalpy and very low cost. Another advantage of this substance is the ability to set the melting point by manipulation of the CaCl₂ concentration. Its biggest problem in the practical application was the durable containerization of this very corrosive substance and its long-term stability. Very few commercial products and buildings were therefore actually created and with the decrease in energy costs these products disappeared again from the market.

In recent years, research focused increasingly on paraffin and fat acids and their use as phase change materials. The use of these materials to dramatically increase the thermal storage capacity of lightweight building materials like gypsum board has been explored and seems to be very promising for the future. Also the use of other PCM materials to reduce peak temperatures in electric...
equipment has led to some commercial products\textsuperscript{34}. Salt hydrates are also still under investigation for their ability to transmit light and to be used in solar applications. Just in recent years research on the combination of calcium-chloride-hexahydrate with commercially available TIM insulation was studied at the Federal Institute for Material Testing in Zurich, Switzerland. This study showed a potential way of using PCM in the building envelope and the associated energy savings\textsuperscript{35}.

\textsuperscript{34} as an example see the products of CLIMATOR, Sweden
\textsuperscript{35} see Manz
4. THE PROPOSED COMPONENT

The understanding of the building skin as a responsive boundary leads to the question of how the aforementioned new materials could be combined to improve the thermal performance of wall assemblies. Obviously, there is an infinite potential for combinations and every climate, building type, program and even orientation need to be investigated separately. Such an investigation could lead to a system of elements or layers that could be combined in different ways according to the specific local conditions. This strategy has already been adopted for the construction industry (see the use of vapor barrier, insulation layers, moister barriers etc. in conventional framing construction) and is the common understanding in the layering of clothing (for example the use of a Gore-Tex jacket layered over a fleece sweater on top of a light moisture permeable polyester shirt). However, this strategy can be taken one step further with the materials discussed in the previous chapter. The interaction of these materials not with each other but also their combined and varied performance effects on the overall building need to be explored. The ideal goal is to develop an understanding of a layered skin as a system of elements with distinctive characteristics that enables designers to create buildings that respond actively to their changing environment.

The starting point for such an investigation should be a specific location, orientation and building program. Most of the developed world is located in climate zones with seasonal changes. In order to validate some of the assumptions made in this thesis Boston, Massachusetts, was chosen as the meteorological context. This location provided a scenario with a substantial heating requirement during the winter and a modest cooling load in the summer (see figure 10 for climate data). It also provided a diurnal temperature variation...
that could be beneficial in balancing some of the extreme weather conditions, through the use of a type thermal mass and transformation in the building skin.

The underlying interest of this investigation is to reduce the energy consumption of buildings. Therefore, the proposed assembly concentrates on a situation in which the environmental forces can be best utilized to achieve this goal. The south elevation of a building, with its high exposure to solar radiation, seems to be the most promising situation for this purpose and was chosen for the investigation.

The context of American residential construction provided a well-established framework for the assessment of energy consumption as well as for the issues of construction, detailing and aesthetics. Even if it initially seems odd to use these advanced materials in the lower cost market of residential construction instead of the high-end commercial market, this building type actually lends itself better to the proposed investigation due to the heating and cooling requirements and the conventional use patterns in residential buildings. There is also a high potential for the use of well-insulated elements and of solar energy. This potential is higher than in commercial buildings where daytime cooling is usually the main concern.

The initial assessment consisted of a building layout that utilized a relatively prototypical floor size. Orientation and proportion that supports the use of solar energy was chosen without being specifically designed for the application of this facade element. This two-story building is assumed to be standard American wood framing construction and has a floor area of 90 sqm. (968 sqft). It serves as the base case against which the performance of the use of such a new facade element is evaluated.

It is critical to understand that the use of such a specific set of boundary conditions is necessary to make an evaluation of the potential benefits of such a
proposed assembly possible. It is not meant to be an optimization for a specific singular case, rather it is an initial numeric assessment that serves as a starting point for further exploration. Results and strategies can be extrapolated from this study for different locations, orientations, building forms and types. The later chapters of this thesis use the findings of the base case analysis to make projections for the future potential of the proposed component in different contexts.

4.1. Strategy of Evaluation

Every part of a building exists within the context of three main categories: performance, integration and design. Performance is usually related to a material or piece of equipment and allows objective comparison of one component to another (the strength of a beam, the efficiency of an HVAC system, the longevity of a carpet). Integration addresses how these pieces are put together and what the implication or trade-off of the combination might be for the whole building (i.e. the implication of choosing a steel structure or a timber structure for the layout of the HVAC system). Here it is much harder to find absolute measures of success since usually a high degree of complexity is involved and there are often ranges of possible solutions. The aspect of design then includes not only the subjective evaluation of what is more beautiful but, even more importantly, how useable and functional the configuration of these pieces are for the user (i.e. what is the implication of using a steel versus a wood structure for the column grid and thus for the floor layout of a space). Here again it is difficult to find absolute measures for the success of a design unless issues are looked at in isolation, which is almost impossible in order to generate designs that satisfy all constrains.
Even if this fundamental understanding of the forces that shape every part of a project is, or at least should be, common in the design of buildings, it is not often apparent in the development of new products or strategies. A strange disjunction happens and developments focus on one of these categories and ignore or under-evaluate the other two. This trend is caused by the high specialization of the professions and corporations involved. The building industry is not yet at a point of collaborative product development like it is utilized for example in the development of most consumer products. Often the realization that the applicability of a new idea is dependent on all three aspects comes late in the development of a new solution. This way resources are wasted and a chance for a more successful and targeted development process are lost.

Initial assessments of a new concept in all three categories can provide guidelines for the refinement of the concept and provide feedback for the general feasibility. Thus opportunities and problems can be clearly identified early and potential paths for future investigations can be established.

Architects are the members of a design team that are usually in charge of satisfying the requirements of all three categories, supported by engineers, cost consultants, contractors and various other disciplines. Unfortunately they are seldom part of the development process of strategies and technologies that are made available to them for the creation of buildings. Based on their experience and training they could make a positive impact in these developments and especially guide this initial assessment.

This thesis establishes such an integrated path and evaluates the proposed component according to the ideas of such an initial assessment. This strategy seems to be especially pertinent considering the innovative nature of the utilized technologies. Instead of analyzing one aspect of the component in great depth
and facing the danger of totally missing a crucial conceptual flaw, the problem is approached from a different angle. All three topics, performance, integration and design, are addressed and the most relevant key parameters in each of these categories are identified. From there, an evaluation of these key issues is established to determine the general performance and feasibility of the proposed component.

By its nature, this approach can be criticized for a lack of thoroughness in the investigation of each category. It is the intent of this thesis to show that for the preliminary assessment of a new idea, this approach is valid and even necessary to guide future research successfully. It is this understanding of the research approach that is maybe the strongest connection to the ideas of the House_n research consortium in which exactly this idea of preliminary investigation as a guide for the industry is fostered.

The proposed component is analyzed first in terms of its performance. This analysis is partly based on available data published by manufacturers and research institutions. Missing information has then been either measured experimentally in MIT’s facilities or approximated based on existing data. This data has then been used in a base case analysis that included a first-pass thermo-dynamics calculation for the element and a standard calculation for the interaction with a building based on standard ASHREA procedures. A qualitative validation of these calculations and assumptions has been achieved by building a prototype element and recording experimental measurements in an environmental test chamber at MIT. This investigation allowed for an estimate of the reduction in heating and cooling loads based on a determination of k- and g-values for the element. The aspect of time lag was also investigated and the benefit of using a thermal storage device in the facade is discussed. Spectrophotometer measurements and light sensor measurements allowed for
an estimate of the solar and visible transmittance of the component and the implications for the lighting design of a space utilizing this component are also explored. This first and rather rough evaluation provided enough information to place the component into the context of other available systems and to compare the potential performance benefits.

In the investigation of the integration implications of the component, the established performance parameter of the base case analysis are used to compare the implications of the component with other existing technologies. Here the energy consumption for heating, cooling and lighting is compared to standard construction based on ASHRAE procedures. The same method is used to assess the benefits in different locations to assess the potential place response of such a system. Based on the available information and experience collected during the creation of the prototype, the anticipated and predicted failure modes are outlined and variations in the assembly discussed. Finally, the discussion of construction issues, including installation, detailing, sizing, maintenance and cost implication concludes this part of the analysis.

The final part of the evaluation process looks closely at the design implications of such a new facade element. Examples for the esthetic implications of the integration are discussed utilizing examples of buildings with similar elements as well as ideas for the installation in conventional construction. The use in different building types is investigated to point out potential variations in the application of the system. The use of the prototype elements and scaled models is the main source of information for the appearance of the combination and conceptual ideas for the variation of the assembly and its construction are explored based on this experience. The goal is to provide an understanding of how such an element would alter the perception of the wall assembly as well as the building itself.
Each of these evaluations is treated as a separate entity and results and potential errors in the evaluation are discussed within the context of each evaluation process. However, strong overlaps exist between all of these categories and the order of this evaluation has been established to allow for a logical sequence of exploration. The combination and overview of the combined results is given in the conclusion of the thesis and a catalogue of issues that need further investigation or improvement is compiled.

4.2. Description of Assembly

The ideal building skin of a heating dominated building should be well insulated and utilize maximum solar energy to reduce the heating load and energy required for lighting. With the materials available today and new materials to be commercially available soon such a building envelope can be designed as a skin of multiple functional layers. The functions to be attained are storage of thermal energy gained from solar energy, thermal insulation to the exterior and control of solar gain. For the purpose of this first attempt to create such an envelope an element was also created that has a degree of translucency to visible light to support interior lighting and to visualize its performance.

The sequence of these layers is determined by their functions: control of solar gain as the most exterior layer to prevent overheating, thermal insulation to prevent the heat loss from the inside and thermal storage as the innermost layer exposed to the interior (see figure 13). Obviously there are other principal configurations possible, but if a combination within one element is desired this sequence is the most intuitive. Based on the initial studies on new material developments one material for each layer was identified: electrochromic glass for control of solar gain, granular aerogel as thermal insulator and calcium chloride...
hexahydrate as a phase change material for thermal storage (see fig. 15). This selection was based on the superior performance of each of these materials and to investigate the potential of these advanced materials in combination. The desire to explore these new materials was a prime reason for this selection, even though other solutions might have been more economical or technically feasible.

The assembly follows the principles of a thermal storage wall with translucent insulation like it has been explored in recent years by the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany. 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 such a combination. The introduction of electrochromic glass in this context is a next step taken to improve the performance of such a wall and adds the advantages of active control of solar gain within the assembly.

In the proposed assembly all three of these materials are combined into one element. The nature of the selected materials and their sophisticated technology and considerations for production process and on-site handling were the primary reasons for this approach. Framing technologies known from conventional glazing assemblies have been used in earlier studies for aerogel windows and proved to provide suitable containers. In the commercial production of the first electrochromic windows electrochromic panes are assembled with a second glass pane into double pane windows. Here again the framing technology is standard window technology well established in the industry. The proposed element uses this technology as a starting point for the detailing of the component. Three layers of glass, two panes of float glass and one

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1. see Beck and Architectural Review
2. based on the construction of electrochromic Windows by FLABEG, Pilkington Ltd. Germany

Advanced Building Skins - S.M. Building Technology - N. Kienzl - School of Architecture - MIT '99
electrochromic glass pane, spaced with aluminum edges and sealed with silicon were chosen as container for the granular aerogel and the PCM. Issues of detailing and problems with this construction are discussed in a later part of this text.

Based on earlier studies with aerogel and this particular type of phase change material, as well as the available framing materials for the prototype elements led to a spacing of 20mm (0.75 inches) between the glass panes and thus for the thickness of the aerogel and PCM layers (see figure 16).

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

For the creation of models and the prototype, samples of materials were collected from the industry or manufactured according to guidelines provided by the companies involved. Granular aerogel was supplied by Cabot Corporation. The phase change material was mixed by combining water and commercially available calcium chloride pellets in a ratio specified by Dow Chemical, to set a temperature of fusion for 26°C. Electrochromic glass was supplied by Pilkington Glass in Germany. Unfortunately, the shipment of electrochromic glass was overshadowed by problems in the transport and operation of the samples. Therefore electrochromic glass could not be included as part of the test chamber analysis. In lieu of this, data provided by Pilkington made numeric evaluations possible.

\[3\] see Beck for aerogel and Manz for PCM
The availability of these advanced materials was a major criteria for the materials used in the evaluation. Variations possible with other material properties based on different products will be mentioned. The available materials and data were sufficient for the conceptual consideration of the proposed assembly.

4.3. Base Case Analysis

The initial performance assessment of the proposed component was explored through a base case analysis. This analysis established a specific construction for the element and set of boundary conditions as a starting point for the discussion of the performance of the element. It needs to be clear that the chosen construction is not the result of an optimization process, but rather the very first step in such a process. The goal was to define the larger issues and potentials of such an element and to find new directions for more specialized research based on shortcomings in the construction or the evaluation process.

This base case was also intended to serve as a point of reference from which variations in the element's configuration or use could be explored. This way changes in the configuration can be related to changes in the performance and can be compared to the departure point. It is therefore important to establish this evaluation with an understanding of the critical parameters as well as the factors that influenced these parameters.

4.3.1. Critical Parameters

The performance of the component has implications on the performance of the building as a whole. For example, the thermal conductivity of the element will influence the heat loss of the building and therefore influence the design of other...
For the evaluation process of the proposed assembly it is important to differentiate when the component is analyzed and when interaction with the larger system is the main concern.

For the component, the total energy flow (radiant and conductive) are the main concerns. This flow is determined by the external conditions of temperature and radiant (solar) energy. The material properties that mediate this flow are the thermal conductivity, the thermal storage capacity and the absorption, reflectance and transmission of radiant energy of the assembled materials. Based on this information, a steady state calculation can determine the energy balance for a single element under steady boundary conditions. Since the energy gain is mainly determined by the values of radiant energy transfer, the validation of these material properties, especially of their combination is a critical aspect for the accuracy of all of these evaluations. Here, the experimental measurement of the materials with a spectrophotometer provides validation of available data. Based on these measurements, further assumptions on the performance of the assembly can be derived.

The overall heat load within the system can be determined by standard ASHRAE degree day method. In this calculation, all gains and losses are determined and an average heat load based on information specific to the location and construction can be established. The sizing and construction of the building and its elements, as well as internal loads, solar gains, ventilation rates and location and climate data are primary parameters. In this context, the thermal conductivity of the element and its supply of additional solar energy has to be accounted for. A comparison between the heat load in standard construction and with the new component installed can be drawn through this calculation. The configuration of the overall system is of primary importance and variations of the system to improve the feasibility of the element can be derived. The measurements of the

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Figure 17: Evaluation matrix for proposed assembly.
thermal performance of the component in a test chamber were used to validate the behavior of the proposed element under real environmental conditions. The changing outside conditions cause changes in internal temperature of a monitored internal space. Although this experiment involved a very simplified system, the performance of the element can be observed and assumptions about the interaction with a real building can be projected.

The result of all of these evaluations is a qualitative assessment of the potential performance of the proposed component that can serve as a guide for improvements and for the assessment of its general applicability. It should be noted that a detailed numerical analysis of the component and its interaction with the building would require a sophisticated simulation of component and system. This simulation technology is currently not readily available and standard building simulation tools like DOE2 or TRANSYS are insufficient for such an evaluation at this time. Thermal storage in translucent phase change materials and the changing properties of an electrochromic glass can currently only be evaluated with individually customized thermal engineering software, a task well beyond the scope of this thesis.

4.3.2. Steady State Calculation

The initial step in the assessment of the thermal performance of the component is the evaluation of the energy flow in a steady state situation. As boundary conditions for such a situation, the winter case is appropriate since heat loss is the greatest during this time. The goal of such an evaluation is the comparison of solar heat gain to conductive energy loss.
The radiant energy gain per square meter can be calculated as:

\[ Q_{in} [\text{kJ/m}^2] = Q_{sol} [\text{kJ/m}^2] \times \text{shading factor} \]

\( Q_{sol} \) can be determined from ASHREA Fundamentals as solar irradiance for the location of Boston in January on a south oriented surface. The shading factor is a value describing the amount of solar energy transmitted through the assembly. Since in the proposed assembly the storage element is part of the wall construction, the shading factor is not the coefficient of the total assembly but just the combined value for EC-glass and Aerogel. Thus, the amount of solar energy that can be collected by the storage material can be calculated. For the EC-glass a solar transmittance of 60% is quoted by Pilkington for the bleached state. For Aerogel, a low value for \( \tau_{sol} \) of 20% can be assumed as a starting point. Based on these values a shading coefficient of

\[ SC = \frac{60 \times 20}{100} = 0.12 \]

can be approximated. Furthermore, these values the solar heat gain can be calculated:

\[ Q_{sol} = 5,300 \text{Wh/m}^2 \times 3,600 \text{s/h} = 19,080 \text{kJ/m}^2 \]

\[ Q_{in} [\text{kJ/m}^2] = 19,080 \text{kJ/m}^2 \times 0.12 = 2,289.6 \text{kJ/m}^2 \]

The heat loss through the component is dependent on the thermal resistance of the layers within the element and the temperature difference between inside and outside. The overall thermal resistance of the element must be calculated in order to account for the total energy flow. The thermal resistance can be calculated based on the thermal conductivity, \( C \), for each layer and their respective thickness, \( d \). For the EC-glass, the thermal conductivity of standard float glass was approximated since no other data on this material was available. The real values for this glass is most likely lower since the electrochromic film
serves as a thermal break between the two layers of float glass. For the phase change material the higher thermal conductivity of solid PCM was chosen. Therefore a conservative estimate for the overall thermal resistance of the element, \(1/\lambda_{\text{element}}\), can be calculated as follows:

\[
1/\lambda_{\text{element}} = (d_{\text{ec-glass}}/C_{\text{ec-glass}}) + (d_{\text{aerogel}}/C_{\text{aerogel}}) + (d_{\text{glass}}/C_{\text{glass}}) + (d_{\text{pcm}}/C_{\text{pcm}}) + (d_{\text{glass}}/C_{\text{glass}})
\]

\[
C_{\text{ec-glass}} = 1.0 \text{ W/m}^2\text{K} \quad d_{\text{ec-glass}} = 0.013 \text{ m}
\]

\[
C_{\text{aerogel}} = 0.02 \text{ W/m}^2\text{K} \quad d_{\text{aerogel}} = 0.02 \text{ m}
\]

\[
C_{\text{glass}} = 1.0 \text{ W/m}^2\text{K} \quad d_{\text{glass}} = 0.006 \text{ m}
\]

\[
C_{\text{pcm}} = 1.1 \text{ W/m}^2\text{K} \quad d_{\text{pcm}} = 0.02 \text{ m}
\]

\[
1/\lambda_{\text{element}} = (0.0131/1.0) + (0.02/0.02) + (0.006/1.0) + (0.02/1.1) + (0.006/1.0)
\]

\[
1/\lambda_{\text{element}} = 1.045 \text{ m}^2\text{K/W}
\]

Taking into account the values for convective heat transfer on the outside (0.029 m²K/W) and inside (0.119 m²K/W) surfaces, the total thermal resistance is:

\[
1/\lambda_{\text{total}} = 1.045 + 0.029 + 0.119 = 1.193 \text{ m}^2\text{K/W}
\]

and

\[
\lambda_{\text{total}} = 1/1.193 \text{ m}^2\text{K/W} = 0.839 \text{ W/m}^2\text{K}
\]

For the heat loss through the element, a mean exterior temperature of -6°C as winter design temperature and a interior temperature of 22°C can be assumed for the selected location\(^4\). Based on these assumptions, the heat loss, \(Q_{\text{loss}}\), per square meter per day through the element can be calculated as:

\(^4\) for values see Stein, Reynolds

Advanced Building Skins - S.M. Building Technology - N. Kienzl - School of Architecture - MIT '99
\[ Q_{\text{loss}} = \lambda_{\text{total}} \times (T_{\text{inside}} - T_{\text{outside}}) \times 24 \text{h} \]

\[ Q_{\text{loss}} = 0.839 \text{ W/m}^2\text{K} \times 28^\circ\text{K} \times 24 \text{h} = 564.8 \text{ Wh/m}^2 \]

\[ Q_{\text{loss}} = 564.8 \text{ Wh/m}^2 \times 3600 \text{ s/h} = 2.033,3 \text{ kJ/m}^2 \]

The balance of this simple steady state model can now be established by comparing \( Q_{\text{loss}} \) with \( Q_{\text{in}} \):

\[ Q_{\text{balance}} = Q_{\text{in}} - Q_{\text{loss}} = 2.289,6 \text{ kJ/m}^2 - 2.033,3 \text{ kJ/m}^2 = 256,3 \text{ kJ/m}^2 \]

This very simplified approach shows an energy gain through the element even during the selected winter situation with its lowest yearly solar irradiance and largest mean indoor outdoor temperature difference. However, this calculation is a very crude approximation. For example, no angular dependence on the solar transmittance of the material has been taken into account, a factor that could change the energy balance quickly to an energy loss. On the other hand, even a slight increase in \( \tau_{\text{sol}} \) for the aerogel could improve the energy balance significantly. Also, the calculation does not take into account that the phase change material will store energy and therefore will maintain a higher temperature within the envelope. To evaluate these aspects accurately would require a detailed heat transfer simulation based on changing temperature and radiation data. Nonetheless, for the initial assessment, it seems suitable to conclude that based on the steady state assessment the system has the potential to produce a net energy gain for the building even in the winter condition for the selected location.
4.3.3. Spectrophotometer Measurements

The amount of radiant energy transferred is the main criteria for the energy gain in the component. It is important to investigate the interaction of materials with different transmission properties to establish an understanding for the implications of a strategy of multiple layers in the building skin. Radiant energy transfer through a material is characterized by the amount of energy that is reflected, absorbed and transmitted. These values are dependent on external factors, like the angle by which the radiation hits the surface and whether it is diffuse or direct light, and are material properties. The response to different wavelengths of the radiant spectrum determines the appearance of a material and its thermal performance.

Published values for solar transmittance, $\tau_{\text{sol}}$, exist for all of the utilized materials. However, to make an informed assessment of their combined performance it was necessary to determine the spectral distribution of the transmissivity of each material. For this purpose the Cary 5 Spectrophotometer with Diffuse Reflectance Accessory, available through the shared facilities in the Department of Material Sciences at MIT was used. The diffuse and direct reflectance and transmission for each of the materials was measured with this equipment. For the electrochromic glass, no sample of appropriate size could be acquired. In this case, Pilkington supplied detailed data on the transmission of their glass in different states of coloring.

Measurements for percent reflectance and percent transmission in the wavelength range from 250nm to 2500nm were taken in 4nm increments for:

- 1/8" (3.1mm) float glass
- 1/16" (1.5mm) float glass
two 1/16" float glasses with a 1/2" (12mm) spacing
• granular Aerogel, 1/2" (12mm) and 3/4" (19mm)
• Calcium Chloride Hexahydrate, 3/4" (19mm)
• Polycarbonate, 1/4" (6mm)

In case of the Aerogel and Calcium Chloride, the materials were enclosed in frames with sides composed of 1/16" float glass. The size of the equipment restricted the maximum size of the samples and special samples to 2.5" by 2.5". Multiple measurements on different points of the samples showed no significant variations. Although problems with the calibration of the equipment in the Near Infrared Range occurred, the measurements were assumed to be sufficiently precise for this investigation and were found to be comparable.

The absorption for the materials were calculated based on these measurements. The sum of reflection, absorption and transmission is known to be one hundred percent. These measurements are presented and discussed on the following pages. The values for solar and visible transmittance, as well as for absorptance and reflectance were determined based on this data and the known spectral energy distribution of solar radiation.
1/16" Float Glass

Solar Transmission, $\tau_{\text{sol}}$: 84%
Visible Transmission, $\tau_{\text{vis}}$: 89%
Solar Reflection, $\rho_{\text{sol}}$: 1%
Solar Absorption, $\alpha_{\text{sol}}$: 15%

The transmission curve of float glass shows a very high transmission in almost all wavelength ranges measured. A strong absorption in the ultra violet spectrum was observed. The extremely low value for the reflectance results from the fact that the sample light hit the surface of the glass perpendicularly, resulting in minimal reflection.

1/8" Float Glass

Solar Transmission, $\tau_{\text{sol}}$: 81%
Visible Transmission, $\tau_{\text{vis}}$: 87%
Solar Reflection, $\rho_{\text{sol}}$: 1%
Solar Absorption, $\alpha_{\text{sol}}$: 18%

As with the 1/16" glass, very high transmittance in the visible and near infrared spectrum were observed, as well as a very high absorption in the UV spectrum. The values follow a similar pattern to the 1/16" glass but with lower transmission and higher absorption. Values for reflectance are almost identical.
2 x 1/16" Float Glass

Solar Transmission, $\tau_{\text{sol}}$: 74%
Visible Transmission, $\tau_{\text{vis}}$: 80%
Solar Reflection, $\rho_{\text{sol}}$: 2%
Solar Absorption, $\alpha_{\text{sol}}$: 24%

Although the same amount of glass material as the 1/8" float glass, the combination of two panes of 1/16" float glass show significantly lower transmission values and slightly higher reflection. This effect is caused by internal reflections between the glass surfaces. Variations in the spacing of the two glass panes had however no recognizable effect on these values.

1/4" Polycarbonate

Solar Transmission, $\tau_{\text{sol}}$: 79%
Visible Transmission, $\tau_{\text{vis}}$: 81%
Solar Reflection, $\rho_{\text{sol}}$: 1%
Solar Absorption, $\alpha_{\text{sol}}$: 20%

The potential of polycarbonate as a container for the phase change material was the main reason for its measurement in this context. It shows clearly the fundamentally different composition of this material compared to glass. Although it shows a higher transmittance in the visible wavelength range than the float glass half its thickness, it absorbs a significant amount of energy in the NIR spectrum. The reflection is similar to glass in all wavelength ranges measured.
1/2" Aerogel

Solar Transmission, $\tau_{\text{sol}}$: 12%
Visible Transmission, $\tau_{\text{vis}}$: 9%
Solar Reflection, $\rho_{\text{sol}}$: 30%
Solar Absorption, $\alpha_{\text{sol}}$: 58%

The granular Aerogel showed a very low transmission and a high absorption due to internal reflections within the granulate. It is interesting that unlike glass or polycarbonate, here the transmission values in the near infrared range are significantly higher than in the visible spectrum. This measurement represents Aerogel within a container. Therefore, the values measured are a combination of these values.

3/4" Aerogel

Solar Transmission, $\tau_{\text{sol}}$: 6%
Visible Transmission, $\tau_{\text{vis}}$: 4%
Solar Reflection, $\rho_{\text{sol}}$: 31%
Solar Absorption, $\alpha_{\text{sol}}$: 63%

As anticipated, a lower transmittance for the thicker sample can be observed and a higher absorption due to increased internal reflections. The value for total reflectance is almost the same as for the thinner sample. Again a higher transmittance in the near infrared than in the visible spectrum was observed.
3/4" PCM liquid

Solar Transmission, $\tau_{\text{sol}}$: 44%
Visible Transmission, $\tau_{\text{vis}}$: 53%
Solar Reflection, $\rho_{\text{sol}}$: 2%
Solar Absorption, $\alpha_{\text{sol}}$: 54%

A liquid sample of the phase change material was measured and a high absorption in the near infrared spectrum can be observed. The measurement shows good compliance with measurements of the same material by Manz in Zurich. No solid sample was measured but based on Manz a similar distribution with a 10% lower transmission and higher absorption, can be assumed.

EC-Glass (Pilkington)

Solar Transmission, $\tau_{\text{sol}}$: 41-2%
Visible Transmission, $\tau_{\text{vis}}$: 48-3%

The data provided by Pilkington shows the various states of an electrochromic glass from bleached to full colored. No values for reflectance or absorption were provided but it can be anticipated that the reflection values are similar to float glass resulting in a very high absorption in the colored state. It was observed that with the coloring of the glass the NIR transmission is effectively reduced.

Overall the data provided by Pilkington results in a much lower transmissivity than usually cited for electrochromic glass (5-65% for $\tau_{\text{sol}}$).
Energy Distribution of Direct Solar Radiation

This graph shows the percentage of total solar energy for each wavelength. This distribution varies slightly for each geographic location and orientation. The data used for this study was obtained from Manz and was the data for Switzerland. Although not specific to the analyzed location, the data was sufficient for the assessment of solar and visible transmissivity.

It can be clearly seen that the main part of the solar energy is located in the narrow range of the visible wavelength range (53%). The amount of energy per wavelength becomes smaller towards the far infrared spectrum. This distribution was used to assess the actual energy transfer through the proposed component.

With the data collected the proposed combination of Aerogel, EC-glass and PCM can be explored. For every wavelength and each layer the amount of energy absorbed, reflected and transmitted can be calculated. Internal reflections were also be taken into account. For this first analysis one internal reflection was considered. As in the steady state analysis, the value for a bleached electrochromic glass was used in order to calculate the maximum energy gain. Since the samples for Aerogel and PCM were contained within glass elements, the actual values and results might differ slightly from actual results for a final component. For an evaluation of the concept and principles it is assumed that these values are sufficient.
Energy distribution within the assembly

This graphic illustrates the distribution of the initial 100% of solar radiation within the assembly based on the detailed calculation of reflectance, transmission and absorption. This calculation took the energy distribution per wavelength into account and matched them with the values measured in the spectrophotometer. T1, A1 and R1 refer to first pass distribution while T2, A2 and R2 represent the secondary transmission, absorption and reflectance based on internal reflections.

The bold numbers at the bottom of the graphic show the overall reflectance and transmission as well as the percent absorbed in each layer.

R=7.1% A=65.0% A=25.4% A=1.2% T=1.1%

The result of this calculation as it is presented shows clearly that with the materials tested the actual energy gain from solar radiation is 2.5%. This value is much lower than the 12% assumed (as shading coefficient of 0.12) for the steady state calculation. The reason for this significantly lower value is the low solar transmittance of EC-glass and Aerogel used for this experimental study. To achieve a value of 12% energy gain with the same EC-glass the aerogel would need to have a solar transmittance of at least 28%, a value not unrealistic with granular aerogel with larger granule sizes. For example utilizing an Aerogel with solar transmittance of 50%, as it has been reported by the Fraunhofer Institute for Solar Energy Systems\(^5\), the solar gain could be as high as 20% even with the EC-glass used in this investigation.

\(^5\) see Marko, page 60-61
Solar transmittance within element with materials used for measurements

This graph shows the solar transmittance within the assembly based on the measurements and calculations for the materials available for the experimental measurements.

The low transmittance after the Aerogel layer shows clearly how the low solar transmittance of 6% of this particular granular Aerogel blocks the energy before it reaches the phase change layer.

Solar transmittance within element with Aerogel with higher solar transmittance

To visualize the effect a Aerogel with a higher solar transmittance would have on the assembly, an Aerogel with $\tau_{\text{sol}}$ of 50% was used as a basis for this graph. It is clear that the improved performance of the Aerogel increases the amount of solar energy available for the phase change material.
An interesting observation is that the result obtained with this detailed calculation varies just slightly (±5% error) from a simplified calculation with overall solar transmittance values. This allows for a faster initial assessment of such a composition without the tedious process of accounting for every wavelength separately. Also, the calculation of one internal reflection proved to be sufficient for the assessment of internal reflections.

The results of this part of the analysis shows that the energy gain with the materials available for the experimental study is too low to make this construction feasible. Nonetheless, it provides a strategy for the evaluation of this type of combination and a starting point to discuss the desired transmittance values needed for a combination that achieves a more feasible performance.

4.3.4. Building Heat Load Calculation

The assessment for the use of the component and its implications on the overall energy consumption of a residential building was explored through a standard building heat load calculation. The chosen method is described in the ASHRAE Fundamentals and other standard publications as a simplified way to calculate the energy consumption based on location, type of construction, use and can account for solar gain in passive solar systems. This type of assessment establishes a middle ground between rule of thumb and full building simulation. It is quick and transparent enough to develop an understanding of the importance of the chosen parameters and can be used to vary parameters easily in order to see their effect on the overall energy balance. The result of this calculation is the amount of energy needed for heating based on the chosen parameters and general approximations established as a basis for this method of evaluation.
The detailed calculations and numbers for this assessment can be found in Appendix 8.4 *Heat Load Calculation - Data.*

For the evaluation, the design of a small residential building was used to determine overall dimensions for windows and wall areas (see Appendix 8.4.3.). The design of this building is based on a competition entry for Trust Joist McMillan in 1994 designed by Professor Chris Luebkeman and Kevin Settlemyre. Standard 2"x6"-R19 American wood frame construction was selected for walls and conventional insulating glass for windows. To account for the use of the component, thirty percent of the south wall was assumed to utilize the proposed facade element. The thermal resistance of the envelope constructions was determined (see Appendix 8.4.9.). Based on an assumed occupancy of the building the heat loss through ventilation was calculated and the buildings overall heat loss coefficient was determined based on infiltration and heat loss through the envelope (see Appendix 8.4.6.).

For the selected location of Boston (see Appendix 8.4.1) the solar energy gain through windows was used to determine the solar heat gain. This value combined with internal heat loads resulted in a total energy gain value for the building. Based on interior and exterior design temperatures the balance point temperature was calculated (Appendix 8.4.7.). This balance point temperature was used to determine a number for Heating Degree Days and with that, the yearly space heating requirements (Appendix 8.4.8.).

To account for the reduction in energy required for heating based on the use of the proposed component the load collector ratio method was used. In this calculation method for passive solar systems the solar savings fraction is determined based on the size and construction of the system and the location of the building. Since only standard values for the construction of reference systems...
are available the value for a heavy mass direct gain system with night insulation was as closest equivalent for the performance of the proposed element. This selection is crucial since it determines to a great extent the outcome of this calculation. Based on this assumption a new value for the yearly space heating requirements was calculated (Appendix 8.4.8.).

The comparison of the two results for yearly space heating requirements shows a 68% reduction (96,948,570BTU / 28,286kWh compared to 30,587,343BTU / 8,956kWh) if the proposed solar gain system is utilized. Even if this value is promising, it needs to be clear that this result should be treated critically. The calculation took detailed data on location, construction and use of the building into account and is plausible in this respect. For the important calculation of the solar gain system however, the selection of a specific reference system had a great impact and adds a great factor of uncertainty. Unfortunately, this method does not provide a way to calculate the real energy savings based on a description of the utilized component. The values given for the reference systems are a combination of empirical and calculated performance results for passive solar systems. The chosen reference system for this case was chosen since it is similar in thermal storage capacity, takes insulation into account and is a direct gain system.

In order to make a more precise assessment of the energy savings, a detailed simulation with hourly weather data and the real performance of the component over time would be needed. Building energy simulation tools like Visual DOE2, TRANSYS and DOE2 are readily available. Unfortunately, none of these tools allow the simulation of phase change materials and electrochromic glazing without the development of customized software. The use of materials with changing properties, like electrochromic glass, would not only require a new material description but also the ability to include a control strategy for this
element within the simulation. Such a control strategy would need to embed the feedback to change the properties of the glass when a certain interior temperature is reached within the simulation model. Such tools can be developed and are crucial for the assessment of these new materials and active building skins. At the current state of development it is however questionable whether a simulation with the available tools would provide results that are more accurate than the simplified heat loss calculation chosen here.

In light of these calculations a substantial energy savings in the heating requirements of residential buildings with the use of the proposed component should be achievable if the amount of wall area covered is great enough. Moreover the cost and feasibility should be compared to other established passive solar systems. However, perhaps the most important realization is that reference values for these new systems or more advanced simulation tools are needed to make precise numeric assessments.

4.3.5. Test Chamber Measurements

A major focus of this study was to evaluate the ability of the proposed component to dampen diurnal temperature swings as is typical for thermal mass systems. The proposed case of a thin layer of phase change material and the use of solar energy through a translucent insulation material however is a significant variation of such a standard system. Therefore, it was of interest to determine the effect 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 on the roof of MIT's Building Three (see figure 18). This endeavor was supported by the Marvin E. Goody Research Award awarded to K. Settlemyre and N. Kienzl by the Department of Architecture in the spring of 1999. The outer design of this facility consisted of an insulated (R19) enclosure in 2"x6" American framing construction. Inside this shell, two highly insulated (R30) control volumes (each 2ft wide, 3ft long and 4ft high) were placed. The outer enclosure serves 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 enclose the 2ft by 4ft openings in which facade components can be installed. The control volumes are surrounded on all five sides exposed to the buffer with rigid insulation and the back walls is removable to access sensors within the control volumes.

For the instrumentation of this chamber measurement devices of the Vital Signs toolkit, developed by University of California at Berkeley, were utilized. HOBO's, small devices that are able to measure and store data on temperature, light intensity and relative humidity, were placed in the chamber and on the exterior (see figure 19). Five measurement series of six consecutive days were taken during the months of March, April and May. The first measurement was taken with the no facade 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. As mentioned before, problems with the delivery of the sample prohibited the installation of an electrochromic window.

The relationship of inside to outside temperature 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. Results of all relevant measurements are found in Appendix 8.5.

These measurements do not allow for a calculation of energy gain and loss as is possible with other test scenarios. 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 could then be used to assess the energy exchange with the exterior. For the purpose of this initial study, as limited by financial and organizational constraints, it seemed practical to allow the interior temperature to float and to derive qualitative results from observations of temperature changes.

In the initial measurement without any element, the interior space 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°C lower, and higher respectively than the exterior (see figure 20 or Data #1.1). A small time lag of around three hours for the temperature swings on the interior were 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.
The introduction of a 20m-thick Aerogel element (see figure 21 or Data #2.1 and #3.1) 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°C higher on the interior than on the exterior. During midday this temperature difference was up to 10°C, due to the high solar radiation 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.

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. Although the Aerogel was the same as in the spectrophotometer measurements and showed the same low transmittance, maximum illuminance levels of up to 2000 L/sqft were recorded for the floor of the control space (see figure 22 or Data #2.4 and #3.4).

For the fourth and fifth measurements, 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 however, the internal temperature swings were effectively dampened by the thermal storage capacity of the phase change.
As a result, temperature peaks on the inside were avoided and the inside ambient temperature changed within a 5°C range while the exterior experienced greater changes. It can also be observed that in cases where the outside temperature changed very quickly to a higher level 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.

Due to the low solar transmittance of the Aerogel, not enough energy was gained to raise the temperature of the phase change material to its point of fusion. Therefore the thermal storage effect that was monitored is sensible heat stored in the mass of the PCM material, not latent heat stored in a phase change. However it can be assumed that in a situation where a phase change would occur 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 become visible.

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 show high lighting levels, but the sensor on the ground of the chamber detected lower illuminance levels with a maximum of 500 Lux/sqm (see figure 23 or Data #4.1 and 5.1). As a result, temperature peaks on the inside were avoided and the inside ambient temperature changed within a 5°C range while the exterior experienced greater changes. It can also be observed that in cases where the outside temperature changed very quickly to a higher level 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.

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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 (see figure 25 or Data #4.2 and 5.2). 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 most likely caused by the high density of the storage material as well as by the thinness of the PCM layer. Energy collected by the storage material is so instantaneously available for the interior.

Qualitative conclusions can be made from the measurements taken with the available samples in the test chamber. It was established that the introduction of a translucent storage element as it is here proposed can raise the interior temperature of a space and reduce interior temperature changes. Even a thin layer of Aerogel and PCM can keep the temperature of the interior at a significantly higher level while providing a limited amount of visible light transmission. Also the higher and more stable inside surface temperature of the PCM element contributes to an improvement in indoor comfort. If due to a higher absorption of solar radiation in the PCM material, the point of fusion will be reached, the beneficial effects of such an assembly should be even greater. This could be achieved with an Aerogel with higher solar transmittance. Based on the here data collected here and previously established knowledge about potential improvements, this concept could be used to significantly lower the energy required for heating. In areas with extreme diurnal temperature swings the damping effect of the PCM could also be used to reduce the energy required for cooling.
4.4. Application and Integration Implications

In the development of a new building component, its integration into a building determines its success or failure. The ways by which a new technology is applied and how its introduction affects other systems, the construction process and the building's operation need to be explored. Based on this experimental prototype, some of these issues can be addressed. Potentials and concerns regarding the integration and application of the proposed facade element are discussed in the following text.

4.4.1. System Implications

The main purpose of this new element is to reduce energy required to heat a building by introducing a translucent facade component. The application of this element to buildings will have implications for the design of heating, cooling and lighting systems. The properties of this proposed assembly are similar to a direct solar gain system with high thermal mass and insulation. The implications on the layout of the heating and cooling system of a building utilizing this new technology are therefore similar to those known from these well-established solar systems.

If properly designed for a building's location and climate, the new component should be able to reduce the energy needed for heating a space by collecting and storing solar energy. This implies that the system will collect enough solar energy to overcome the heat loss of the building to the exterior. The sizing and design of the facade elements is therefore based on a prediction of environmental conditions under which they should perform accordingly. The design is based on a set of likely boundary conditions that account for seasonal and diurnal temperature changes as well as known solar irradiance values.
However, since meteorological conditions are constantly changing, the actual boundary conditions might differ substantially at certain times. To account for such extremes would mean over designing a solar gain system for most of the time it is in use. As for other solar energy buildings, the most sensible solution is to design the components so that they perform under most conditions and to install a backup system for heating during extreme external conditions.

This strategy implies that the heating system must be designed to provide heat during short periods of time to support the base heat provided by the solar system. Thus the heating system can be designed with a lower overall performance and should to be able to react quickly when needed. Most of the time such a backup heating system would not be operational at all and it should be decided on a case by case basis whether a real heating system or even just local heaters are the appropriate strategy.

In the special case of using phase change material as a thermal storage device, it is important to realize that the temperature of fusion of the PCM is the temperature at which the most energy is stored. Unlike materials that store sensible heat, PCM’s are predefined as systems to support heating or cooling. For example, a PCM with a temperature of fusion of 26°C will collect large amounts of energy at this or a higher temperature. As soon as its surrounding temperature drops below this point, it will release this heat again. This is a desirable situation for heating a space. However, if the same PCM would be cooled, for example by cold night air, to reduce a high day-time peak temperature, the amount of energy stored below this point of fusion is sensible heat stored in the small mass of the PCM. The energy stored at lower temperatures is therefore very small. In this respect, the behavior of phase change materials is fundamentally different from heavy mass storage systems that store the same amount of energy at all temperatures. The implication of this
special characteristic of PCM needs to be addressed in order to choose the
desired point of fusion and appropriate cooling and shading strategies.

For the design of the lighting system the light transmitted through the facade
requires evaluation. The most important aspect in this context is whether the
control of the electrochromic glass is connected to the indoor lighting or
temperature situation. Since the amount of light transmitted through the
electrochromic glass determines the heat gain as well as the indoor light levels, it
must be clear which of these aspects has the higher priority. In most cases the
thermal energy gain will be the overriding parameter since energy consumption
for lighting is comparatively low to heating or cooling energy. The implication of
such a priority is that the natural lighting level on the interior will depend on the
thermal situation and might at times need to be supported by artificial lighting. It
can be anticipated that with the use of this facade component the lighting for the
interior will be supported by light transmitted through the element. Nonetheless,
an appropriate lighting system needs to be designed for times when for thermal
reasons all light is blocked from passing through the element.

In this context the control of the electrochromic glass becomes very important
and adds a level of complexity. Since the glass can change gradually from clear
to dark, the process of collecting solar energy can be precisely adjusted. This
way the same amount of solar energy could be collected in a short period of time
when the glass is bleached or over a longer period of time when the glass is
colored. Thus, energy gain and indoor light levels might be optimized together
requiring a sophisticated control logistic. Moreover user interaction with such a
control system becomes an important issue. For example, occupants individually
adjusting lighting levels via the electrochromic glass would have direct impacts
on the energy gain and thus the performance of the overall system. It must be
clear that such a shading device acts more like a thermostat than a blind and
therefore interference with it must be a conscious or automated activity. Lessons learned from the installation of automated building systems in commercial buildings might serve as an interesting source of information to predict how occupants would accept such systems.

4.4.2. Failure Modes

Possible failure modes within the component and and implications of these failures for the building must be identified. Apart from the common issues like water leaks through improper installation or damage through external impacts, potential failures for each of the layers can be identified.

For the electrochromic glass the destruction or degeneration of the electrochromic film are the main concerns. The sensitive film that facilitates the change in transmittance can be damaged through a destructive charge of electric energy, exposure to moisture, degeneration through extensive use and exposure to excessive heat. Control of electricity, sealing and longevity are characteristics that need to be guaranteed by the producer for a sufficient period of time. Excessive heat is however relevant to the proposed assembly and deserves closer investigation. In the proposed assembly the EC-glass is layered in front of the highly insulating Aerogel. Thus the temperatures reached during high solar radiation and full coloration of the glass can be substantial. No exploration of this topic has been carried as part of this thesis and no information on the heat resistance of EC-glass was available. However this issue is crucial for the feasibility of this component and needs further investigation.

Aerogel is very stable even if exposed to moisture and its performance should not vary over time. The main concern for Aerogel is the appropriate container. Even though Aerogel is stable, like glass, in a wet environment, its thermal
properties would rapidly decrease if it would be exposed to humidity due to a higher convective heat flow. Therefore, the sealing of the Aerogel container is crucial for its performance over time. Also the slight vacuum of one bar negative pressure of Aerogel windows needs to be sustained. This pressure increases the thermal performance and prevents movement of the glass panes during temperature variations. This movement of the glass has been a problem in earlier prototypes and caused a mechanical deterioration of the fragile Aerogel. The longevity of such a sealant would need to be guaranteed by the manufacturer of the component. Unfortunately, as with other high performance windows, the actual performance of these sealants is difficult to test after installation.

The most failure-prone component is however the phase change material. The performance of salt-based phase change materials, as they are suggested for the proposed component, is dependent on a uniform mix of salts and water. Unfortunately through repeated thawing and freezing cycles these substances tend to dissipate, an effect accelerated if the volume of PCM is increased\(^6\). Through the addition of various chemicals and the containerization in smaller volumes this mixture can be made more stable and Lane reported salt based PCM with over five thousand cycles without a change in the composition. Lane also reports similar successes by containing PCM in a hydrogel, thus creating micro PCM containers within the gel structure. As long as the concentration and distribution of salts is stable the phase transition should be possible for unlimited cycles. However, if the concentration changes a change in temperature of fusion is the result, rendering the PCM useless for its specific application. Interestingly even if the distribution of the salt changes, in most cases it just settles to the bottom of the container, a simple mechanical stirring of salt and water will recreate the initial condition.

\(^6\) see Lane for indepth discussion of salt-based PCM's
Another source of potential failure for the PCM is its container. Salt-based PCM’s experience a change in volume of up to ten percent during phase transition. Therefore, the container must be appropriately designed to account for this change without breaking. Also the corrosive nature of the salt makes the use of metal parts in the container problematic. Finally, it needs to be considered that the PCM after its phase transition is in a liquid state with inherent problems. Especially in the design of building envelopes, where one of the prime concerns is to keep precipitation and moisture out, the introduction of a container filled with liquid is a challenging task. The sealant and resistance to impact on the container become increasingly important to avoid moisture damage to the building.

For electrochromic glass and PCM performance over time is highly relevant, since both of these materials constantly change their state, which can lead to a decreased performance from repetitive use. Tests on the longevity of these materials should be carried out to ensure a lifetime that would make the use of such a component economically, technologically and ecologically feasible.

All of these described failure modes would result in a severely decreased level performance and would have serious implications for the building. The destruction of the electrochromic film would eventually lead to an increased heat gain, a decrease in thermal resistance of the Aerogel would lead to rapid heat loss and dissipation within the PCM would reduce the thermal storage capacity. As a result, even the failure of one layer would reduce the performance of the overall element significantly. Slight changes in the properties of one of these layers might even be acceptable but a severe failure of even just one layer would necessitate the replacement of the whole component. This consideration could lead to the separation of the materials into layers that could be individually replaced.
4.4.3. Place Response

The proposed component has the ability to respond to changes in the environment by changing its transmittance of solar radiation. Even though this is appropriate for adjustment to local climatic variations, it is possible to adjust the properties of the component for use in different locations. If the same set of materials is considered, parameters within the component can be varied to achieve a better place response. The two layers that can be adjusted are the Aerogel and the PCM layer. An increase in thickness of the Aerogel insulating layer will result in a higher thermal resistance of the component and a lower conductive heat loss. It will however also reduce the amount of radiant energy transmitted due to a higher absorption within the Aerogel. An increase in the thickness of the PCM layer will result in a higher thermal storage capacity but also in a lower transmittance of visible light.

Both of these adjustments show very clear trade-offs and it might be that a very narrow range of adjustments would make sense for such a combination. Another place response adjustment is to reduce the number of layers and, for example, not to include an electrochromic glass in colder climates where no excessive heat gain is anticipated. The amount of higher transmittance gained through the elimination of this layer could be used for a higher direct gain or to increase the insulation value accordingly.

Even with the same component a response to local conditions could be achieved by utilizing different amounts of the element or by orientating the building differently. For all of these aspects, however a detailed study of the performance of the component under specific climatic boundary conditions need to be executed. For this purpose, as mentioned before, the development of simulation tools for such advanced elements would be necessary. With such tools the
component and its interaction with local weather data, design priorities, building form and construction could be simulated. Without such an assessment it is almost impossible to make recommendations on sizing and configuration for a specific situation.

4.4.4. Construction

The actual detailing of such an advanced building element must be developed by the building industry with consideration for production capabilities as well as general production cost, issues of performance, and engineering involved. This development will respond to the market demand and technical constraints of the firms involved in this development. However, based on the conducted research some general assessments regarding the construction, installation and maintenance of the proposed element can be derived.

Process

Unlike most other building materials, none of the materials in this component can be manipulated during the construction process. For example, EC-glass must be assembled, wired and sealed in a clean environment. The same holds true for Aerogel and PCM in order to guarantee their performance. As a result the proposed element must be a completely prefabricated unit that is installed on the building site like an insulated window or other more complex components. Although this requires a more advanced planning process, since elements need to be ordered and delivered to fit, it also reduces the complexity of the installation of the component.
If the element is properly designed, there should be no special requirements for installation. Only the wiring and connection of the EC-glass to a building control system requires additional effort. However, this task should be comparatively easy for electricians that usually install the more advanced home automation and control systems in place in most high-end residential buildings. Considering systems with a complex bus-technology, like Honeywell, Siemens and other firms currently selling, the integration of these new components should not be problematic. These systems would be appropriate for the control of an advanced building skin since they can combine various systems within one bigger control strategy. Also, the extra cost required for wiring the element is anticipated to be low, since most high-end buildings already contain wiring for burglar alarms and automated blinds along the building facade.

One of the biggest issues in the construction of an advanced facade element is the identification of an actual producer. Three main areas of expertise are involved: glass technology for the EC-glass, chemical engineering for Aerogel and PCM, and window technology for the production of an appropriate assembly. The combination of this expertise becomes a main organizational issue. Unlike other window technologies, where smaller companies can use the basic float glass provided by glass plants, to fabricate insulated window units, the processes here are more complex and require a higher degree of equipment and engineering. Still, such specialized firms are the most likely candidates to combine the base materials provided from other industries to create feasible building product. However, without stronger efforts to produce larger quantities of the appropriate base materials the economic feasibility of such elements will be hard to achieve. Therefore it seems that bigger corporations in the industry must get involved to push this development ahead.
Detailing

In the detailing of the proposed element the biggest conceptual issue that needs to be resolved is whether one integrated component or a system of separate elements is the more feasible solution. As in the discussion of failure modes, the separation into layers might be a reasonable approach to deal with issues of replacement and to account for different life times of the various layers. The advantage of a single element however would be a simpler installation and delivery process.

If a system of elements is considered it seems reasonable to combine EC-glass and Aerogel into one unit and to keep the PCM as a separate element. This approach was also chosen for the prototype element. The technologies needed for EC-glass and Aerogel are similar and similar life spans were assumed. PCM will need a different technology for its container to account for safety issues and to adapt to the phase change process. The issue of different life spans could also be addressed this way and a solution in which the PCM element is exchanged quite frequently while the EC/Aerogel component remains fixed might become feasible.

The detailing of EC-glass and Aerogel windows\(^7\) has been explored in recent years and a combination of these two technologies into one element, similar to a conventional double-pane window seems absolutely feasible. The EC-glass would require a frame around its edges to cover and protect the wiring that supplies the electricity to the electrochromic film. This frame element would include the connectors to the wiring of the building.

The detailing of the PCM element is not yet resolved and needs further investigation. Two main problems can here be identified. First, the issue of

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\(^7\) see Architectural Review, Marko
dissipation of the PCM requires that it be enclosed into small containers within a larger element or the mechanical stirring of the mixture in certain intervals is predominant. The research on gel based systems might provide a successful pathway for containerization. The concept of a mechanical mixing of the PCM while it is installed is unrealistic even facade systems that include circulating fluids have been proposed in recent years. If the PCM component is kept separately from the element it could however make sense to install it in a way that it could be easily removed. Since this layer is located behind the actual exterior skin this should be fairly easy to achieve without problems of leakage or thermal issues. This way the PCM could be treated as a replaceable element and the low cost of the PCM and a recycling or reuse scheme could make such a concept feasible. A scenario in which a local service company would remove the PCM element every other year to refill them with fresh PCM by reusing the old filling could be quite reasonable. The concept of such heat packs in the facade, not unlike the cool packs used on a smaller scale for sport injuries, might not only influence the detailing of this element but also a cyclic understanding of the building skin.

The second issue that can be identified with the PCM container is the problem of volume change during phase transition. In the prototype element this issue was resolved by leaving a sufficient air space within the PCM container. This resulted in an uneven light distribution and heterogeneous appearance of the element. To resolve this problem either the container needs to be able to expand and contract or some other form of pressure release needs to be found. The use of polycarbonate or other plastics in the construction of the container could provide such flexibility and reduce the risk of shattering under higher internal pressures. No

8 see, McKee, London
studies of this aspect were carried out as part of this thesis but should be a substantial area of future research.

Sizing

Sizing of the proposed component depends on the material characteristics as well as its integration. In general large elements would be beneficial since then the effort for wiring and connections to a building control system would be reduced. Also the heat loss through frames and edges would be reduced, increasing the thermal performance of the element. However larger volumes of PCM show the previously discussed accelerated problem of dissipation. Also in larger volumes Aerogel tends to settle more over time, due to its loose granular structure. Even if theoretically very large panels could be produced a realistic approach for the near future are medium-sized elements that adhere to standard modules used in the construction of residential buildings. Element sizes of 2ft (60cm) by 4ft (120cm) or even 2ft by 6ft (180cm) seem to be reasonable if a solution for the containerization of PCM is achieved. These elements could ultimately be integrated as horizontal or vertical elements in the facade.

Maintenance and Operation

The operation of the element needs some form of control, whether individually controlled through a feedback system that adjusts solar gain based on internal temperature of a room or even the PCM, or via connection to a more elaborate building control system. Various scenarios and control strategies would need to be tested and simulated to optimize the performance for special climates and usage of buildings. For the operation of the EC-glass just low voltages of 3 Volt
and low amperage to change the opacity are needed. In case of a power outage the glass would just be fixed in its most recent state. Other than this the maintenance of the EC/Aerogel part of the component would be similar to the maintenance of a normal window. Cleaning of the surfaces would be the only upkeep required for the lifetime of the element.

As discussed before the maintenance of the PCM however is dependent on the final solution found for the longevity and containerization of the PCM. Solutions could range from a stable element with a guaranteed performance for ten to fifteen years to the idea of the frequently replaced PCM packages. The solution available will determine to a great extent the feasible cost of such a component and its maintenance cycles. However during the time when it is installed and operational this element should require no additional operation or maintenance except the obvious cleaning of the surfaces.

4.4.5. Cost Assessment

The assessment of the cost involved in production and installation of such an advanced component is very difficult due to the innovative nature of the utilized materials and the uncertainties in its actual design. Material prices quoted for electrochromic glass, and granular Aerogel by the manufacturers are still prices for small production runs or in the case of Aerogel, not even commercial prices. Estimates on the cost reduction of these materials through larger production volumes have been made\(^9\) but are still very vague. Also the cost of production for PCM, in which the base materials are the widely available calcium chloride and water, the cost of additives and production cannot be assessed at this point.

\(^9\) see Carlson on cost of Aerogel production
Even if material prices would be available the cost for the container or element could not be reasonably assessed as part of this thesis, since too many questions in the nature of the container are still unanswered. After resolving all of the discussed issues the production costs would need to be assessed in collaboration with a potential producer based on their cost of labor and equipment use. In this sense the cost estimate is similar to other consumer or industrial products and does not follow the patterns established for conventional building trades.

It can however be anticipated that the cost of the final element and its installation would be significantly higher than for a standard wall construction and it is unlikely that due to low energy prices the energy savings alone would justify the extra cost any time soon. Nonetheless as can be seen with other aspects of the building's construction, cost is not always directly related to performance. Clients tend to be willing to spend more money on components, ideas or technologies they feel strongly about. Such new responsive skins could raise the excitement for this new technology to a level where the extra cost is just accepted. A prominent example for such a change in attitude is the increased use of titanium as cladding material in recent years. The use of this material is not determined by its performance versus cost relationship but mainly by the visual aesthetic qualities it adds to a building, as exhibited by the architect Frank Gehry for the Museum of Modern Art in Bilbao.

In the context of sustainable building technologies it seems more important to ask what the embodied energy of the element is and how it relates to its implied energy savings. This question should be far more crucial than the actual dollar values of the energy savings versus investment into this technology. Unfortunately due to the proprietary nature of these technologies no information on the embodied energy of these materials was available. Often it was also not
even yet investigated by the companies involved in the production. Therefore an energy balance could not be conducted at this point but should be a crucial part of the assessment of such a product before its commercialization.

4.5. Design Implications

The introduction of the proposed component into a building would have implications for the layout of building systems and the overall performance as previously discussed. As a result, it would also have significant impact on the appearance, layout and configuration of the building. In the following text the applicability and implications of the proposed component for different building types and uses are discussed. Concluding this section is a discussion of the implications for the appearance of the building envelope and how this new component can change the perception of the wall.

4.5.1. Component and Building Type

The biggest issue for the integration of the component into various building and construction types is that the component is not able to carry vertical or lateral loads. In this respect it is similar to other glazing systems and has similar implications for the design of walls. Thus, the building needs a structural system or framework that can support the weight of the components, withstand or transfer wind loads on the facade and carry all vertical and lateral loads in the wall without transferring stress to the components. This is particularly important if we consider the elements not as a small portion of the wall, like a conventional window, but as a substantial part of the envelope.
In American residential buildings the predominant construction type is standardized wood or metal stud framing. In this construction system the exterior sheathing, usually plywood, carries lateral loads providing stiffness to the building. If large portions of this structural layer are replaced by the proposed component the structural integrity of the wall will be reduced. Therefore it must be clear that the integration of such a new wall system has implications on the distribution of loads within the envelope. Solutions for this problem could be the introduction of bracing members or the distribution of lateral loads on the building through other structural elements throughout the building.

This change in structural capabilities of the wall for this type of construction increases the efforts necessary to integrate the component. Nonetheless the standardized framing system is advantageous for the use of a prefabricated element since detailing and module sizes are very well defined. Elements could be fitted within the 12” to 24” spacing of the 2”x6” members of such a wall either within its own frame, like conventional windows, or directly as a cladding system, as with glass in some newer timber constructions. These considerations might make the use of the component even feasible as a retrofit for existing structures, adding solar heat and thermal mass to otherwise very lightweight structures.

Utilizing an appropriate framing layout the application of the proposed component should be technically feasible for most detached single or multi-family houses. Especially if a larger timber frame structure is chosen, instead of closely spaced stud framing, the proposed component is very applicable. The timber frame is usually designed to carry the vertical and horizontal loads, freeing the skin of structural constraints. In this context non load bearing envelopes are appropriate and the proposed element would fit well into such a type of construction.
The use of the component for bigger building complexes or apartment buildings is also possible. Here again the structural issue is of great importance. If the wall of the building is designed as a load bearing brick or concrete wall the use of the component is limited for structural reasons to the covering of smaller openings within such a wall. Whether the amount of energy gained through such a small percentage of wall coverage is sufficient to make the introduction of such an element economically feasible needs to be evaluated on a case by case basis, but seems unlikely.

However if a larger building is designed utilizing a concrete or steel frame structure the use of the proposed component as cladding could be very feasible. Here the structural requirements for the skin are limited and larger areas of the surface could easily be covered with a solar gain system. In general, a structural system that does not rely on the skin for structural purposes lends itself better for the integration of this new element.

With respect to the building type for which this concept would be applicable a direct relationship exists to the general heating requirements of the building. For cooling dominated office and other commercial buildings the use of such a solar gain system might not be the appropriate solution. However, if due to a lack of internal heat loads or exterior conditions a building requires heating then the introduction of such a system can provide substantial energy savings. As with other passive solar systems the feasibility of a direct gain system needs to be examined based on solar exposure of exterior surfaces to overall building volumes, as well as building layout and internal loads. Thus, the use of the component is not so much determined by the building’s function but by its structural system and its energy requirements.
4.5.2. Other Uses

The characteristics of the component, based on its assembly and selected materials, allow for a unique performance of this new building skin. These considerations make it applicable for a south facing exterior wall. However, if the arrangement or the performance of the layers is changed this component could be used in different locations in a building for different purposes.

With an appropriate amount of energy collected the element could be used on the west, east and maybe even north wall. Here the element would serve the same purpose as a translucent storage element if enough solar radiation is available and a positive energy balance for the building could be achieved. A similar consideration holds true for the use of the element in skylights, since the light diffusing qualities of the element might be beneficial to create very uniform indoor lighting situations.

If variations in the composition of the assembly are considered, even more uses might be feasible. The most apparent variation would be the elimination of the phase change material. This would transform the element into a light diffusing well insulated facade panel with the ability to control the solar transmittance. Such an element could be used in all orientations of the building envelope where no visible connection with the exterior is desired. For the use in skylights, this seems to be very applicable.

The elimination of the electrochromic glass would be a feasible and economical solution for climates where excessive heat gain is not anticipated. The element’s ability to collect solar energy would be increased, due to higher solar transmittance, but no control over the heat gain could be achieved.

The elimination of the Aerogel, however would not be sensible, since the thermal properties of the component would decrease dramatically. However the Aerogel...
could be replaced with another translucent insulation material. This would increase the overall thickness of the element, due to the lower performance of other insulation materials, but could provide a economically feasible solution for the near future. The function of the component would however not be changed by such a substitution.

Due to its characteristic ability to store and control solar energy, the use of the component on the interior or for cooling purposes is inappropriate. Also, since the element is light diffusing and translucent, it cannot be used as replacement for windows in which transparency is desired.

4.5.3. Appearance of the Component

The proposed component differs substantially from other thermal storage walls or direct solar gain systems in its appearance. Instead of including a massive and opaque thermal element the component is a comparatively thin, light-transmitting element with a changing degree of transparency. Thus, the wall becomes a integrated skin that will change its color based on its performance requirements. This active skin will be an indicator for exterior conditions as well as for the interaction between the exterior, the skin and the interior.

A striking aspect of the wall is its light diffusing quality. The granular structure of the Aerogel provides a very even and diffuse light distribution and based on Raleigh scattering within its pore structure the passing light has a slight reddish tint. This creates a warm and comfortable lighting effect for an indoor space, and creates the appearance of a slightly glowing wall, revealing the energy and warmth provided by the thermal storage elements.
The phase change material adds yet another visual quality to the component. During the freezing process the phase change material used for this experiment forms white crystalline structures. These structures change constantly during the phase transitions and provide a unique texture to the surface of the wall. Not only is this texture visible on the exterior of the element but it also effects the light transmitted through it, creating patterns of light on the surface of the element.

This combined, constantly changing appearance of the element is fundamentally different from the appearance of other building materials. Unlike most materials, which can be perceived as stable or slow changing through weathering, this new component is dynamic and almost alive in its constant reaction to external stimuli. It becomes a skin, not only because it encloses but also because it actively mediates interior and exterior.

Based on this new design quality and the considerations for the amount of wall area covered for a substantial energy savings, the new component needs to be strategically placed in the design of an exterior facade. Although it could be used as other solar systems, such as systems with translucent insulation materials, it is more challenging to use the new component in a more innovative way. The component could be envisioned not as part of the wall but as the wall itself. Thus, it would no longer be a patch of active skin in an otherwise conventional design but it would become an active skin with patches for openings and windows. The design quality of such a wall would be similar to systems with light diffusing glass block walls as often found in warehouse constructions. Here windows are consciously placed to create visual connections with the larger part of the wall as a translucent light source. The appearance would be also similar to the Kallwall systems in which light diffusing, insulating panels are used for commercial or industrial facilities.

Image 52: The wall construction of MIT's Center for Advanced Visual Studies, creates an indoor environment filled with diffused light and direct vistas through the use of glass block and integrated windows. Appearances similar to this could be created with the proposed element to provide thermal comfort and visual connections.
Even if there are similarities with these existing technologies the appearance of the proposed element will be fundamentally different. The exterior will be constantly changing due to the dynamic properties of the element. During the day a facade utilizing this technology might appear almost white at certain times, turning slowly to a bluish gray when it gets warmer and starting to glow from the inside as night falls and interior lights shine through to the exterior. In later hours of the night this glow will start to diminish as more and more phase change material turns solid thus reducing the light transfer from the interior, displaying the reduced energy content in the skin.

This incredible richness in the appearance of this skin has the potential to push this technology ahead. It provides designers with new means and new concepts to design buildings with active enclosures and thus with a multiplicity of appearances. A desire to utilize such dynamic building skins might create a market and demand for the development of these technologies beyond the considerations of energy savings and cost constraints.
5. CONCLUSION

In light of the rapid depletion of earth's fossil fuels and the related 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 proposed facade element revealed potential for an assembly that can reduce the energy consumption required for heating residential buildings. To achieve this energy reduction, the proposed assembly utilized new materials and a strategy of active solar control. However, even more significantly, through this new strategy the building skin takes on a new functional as well as aesthetic quality. This added quality of an active and responsive building envelope that adjusts to the changes in the environment can heighten our understanding of the important role buildings play in our interaction with the natural environment.

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. The new design quality could become the driving force behind innovative building technologies. In a context where affordable energy is too readily available, the new aesthetic qualities as well as the environmental benefits of this strategy are the most powerful incentives to push energy efficient technologies forward.

To facilitate such changes research needs to be carried out to make new materials and technologies feasible and to integrate them into the built environment. The chosen evaluation for the proposed assembly proved to be successful as an initial assessment of the 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 facade strategy. Evaluation of the light quantity and quality transmitted through the new element was possible through observations in the test chamber. These results were surprisingly high, considering the low predictions for radiant energy transfer derived from detailed spectrophotometer measurements of the utilized materials. Based on this study potential areas of future research and development to be identified.

From a materials perspective, the most crucial development needed to further the ideas explored in this thesis is the development of stable and effective phase change materials. Research in this realm of material sciences almost stopped in the early 1980's and some of the most interesting opportunities for new ideas are still unexplored. With new tools now available to material scientists to design and evaluate new materials, breakthrough developments could be at hand if the research to develop them would be supported. Other developments like improvements in electrochromic glass, Aerogel, sealant technologies and containers seem to make slow but steady progress. To guide industries in the development of Aerogel clarification of desired performance in terms of transmittance and thermal resistance is required. Now designers need to take advantage of these opportunities to create new specifications and applications.

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 calculations seemed appropriate. However, computational tools would allow for a much more precise assessment of the implications of a certain material composition or control strategy on a building's energy use and thermal performance. The development of tools to assess the component in isolation and within its context would not only allow for more precise predictions but also allow for the quick comparison of alternatives.
Such tools could support and validate the work with an experimental test chamber although not completely eliminate the need for such physical testing. In the process of this project the actual work with the element in the test chamber, its construction, integration and appearance provided valuable insights and made the enormous efforts for its construction worthwhile.

Most importantly, projects that start to use these concepts need greater exposure to push these new ideas ahead. By publicizing these new ideas and by challenging the preconceived notions of the building envelope, a demand for such technologies could be created. This would result in increased efforts in the industry to develop products and systems. Designers and clients must step beyond the boundaries of conventional construction and design to look for new solutions in the wealth of new opportunities available.

This way the principal ideas of how we can live and enjoy our natural and built environments can be expanded and integrated into more sustainable ways of designing, constructing, and using buildings. The ideas of the Modern Movement and their fascination with light, sun, openness and their effect on a more open and democratic society, made possible through new technologies, can be realized without the penalties of destructive resource consumption. This vision of how the integration of architecture with the environment can and will effect our culture has been described by Paul Scheerbart in 1914 in his book Glasarchitektur. Based on present knowledge his vision holds true if designer and engineers can synthesize the use of glass with new materials and technologies discussed in this thesis:

... we live for the most part in closed rooms. These form the environment from which our culture grows. Our culture is to a certain extent the product of our architecture. If we want our culture to rise to a higher level, we are obliged, for better or worse, to change our
architecture. And this only becomes possible if we take away the closed character from the rooms in which we live. We can only do that by introducing glass architecture, which lets in the light of the sun, the moon, and the stars, not merely through a few windows, but through every possible wall, which will be made entirely of glass - of colored glass. The new environment, which we thus create, must bring us a new culture.\footnote{Paul Scheerbat, 1914, from Wigginton, page 01.52}
6. BIBLIOGRAPHY


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7. PHOTO CREDITS

Image 1: Behling, page 145
Image 3: Behling, page 48
Image 4: Behling, page 39
Image 5: Fitch, page 17
Image 6: Behling, page 156
Image 7: Fitch, page 204
Image 8: Peters, Ackermann, page 55
Image 9: Button, page 174
Image 10: Herzog, page 2
Image 11: Campagno, page 110
Image 12: Campagno, page 111
Image 13: Herzog, page 125
Image 14: Herzog, page 109
Image 15: Herzog, page 109
Image 16: Herzog, page 67
Image 17: Herzog, page 122
Image 18: Elliott, page 114
Image 19: Wigginton, page 01.20
Image 20: Elliott, page 139
Image 21: Wigginton, page 02.63
Image 22: Wigginton, page 02.53
Image 23: Wigginton, page 02.69
Image 24: Wigginton, page 03.212
Image 25: Herzog, page 197
Image 26: Marko, page 52
8. APPENDIX

8.1. Material Producers and Research Institutions

The following list of companies and institutions was compiled during the preparation of this thesis and is provided to allow the reader to follow future developments of the technologies discussed. However, it must be understood as a starting point that does not claim to be exhaustive. Most of these technologies are still under development and cited companies or institutions might at any point abandon their efforts in this area or, even more likely, new companies might start to develop technologies and products. Especially in the field of research the efforts are very dynamic and singular so that it is impossible to give an all-encompassing presentation of the research efforts in all these fields in the scope of this master thesis.

AEROGEL

Producers
- Airglass, Staffanstorp, Sweden
- Jet Propulsion Laboratory, NASA, Pasadena, CA, USA
- Lockheed Aerospace, Palo Alto, CA, USA
- KEK, Tsukuba, Japan
- Matsushita Electric Work, Osaka, Japan
- Marketech International, Pittsburgh, PA, USA
- Super Conductor Materials, Suffern, NY, USA
- Aspen Systems Inc, Marlborough, MA, USA
- Keller Companies Inc., Manchester, NH, USA
- Customs Sensors and Technology, St Louis, MO, US
- Cabot, CAB-O-SIL Division, Hanau, Germany
- NanoPore, Albuquerque, NM, USA
- SET, Bereldange, Luxembourg

Research Institutions
- Lawrence Livermore National Laboratory, CA
- Lawrence Berkeley National Laboratory, Berkeley, CA
- Physikalisches Institute der Universität Würzburg, Würzburg, Germany
- Technical University Denmark, Dept. of Building and Energy, Lyngby, Denmark
- Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany

ELECTROCHROMIC GLASS

R&D Organizations?

North America
Donnelly Corp. (USA)                    Dow Chemical (USA)
EIC Laboratories (USA)                  Enermodal Engineering Ltd. (Canada)

? as published by Lawrence Berkeley National Laboratory in the final project report for Project 3B, Chromogenic Glazing under IEA Task 18
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**PHASE CHANGE MATERIALS**

Research on Phase Change Materials has a long history and the base material for the production of salt hydrate PCM's are standard high volume products in the chemical industry. Therefore only companies that produce specific phase change materials and their applications are mentioned here. The only exception from this
rule is DOW Chemical, which had a strong interest in phase change materials over the last twenty years. George A. Lane, formerly with DOW, provided valuable input to this aspect of the thesis.

**Producers**

DOW Chemical, US  
Frisbee, US  
Climator, Sweden  
PCM Technologies, US

**Research Institutions**

University of Dayton, US  
Lawrence Berkeley National Laboratory, US
### 8.2. CONVERSION

#### Temperature

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<td>y*0.17612</td>
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8.3. EXPLANATION OF TERMS

The terminology used in this thesis is based on ASTM C168-90, Standard Terminology Relating to Thermal Insulating Materials. In addition to this terminology this appendix lists terms that the reader might not be familiar with. Especially non-native English speakers might find this explanation helpful for their understanding of the text. For this reason even words that are not necessarily part of the scientific vocabulary but also not commonly used in everyday conversations are listed.

angstrom : a unit of length equal to one ten-billionth of a meter (10 angstrom = 1 nanometre)

autoclave 1 : an apparatus in which special conditions (as high or low pressure or temperature) can be established for a variety of applications; especially 2 : an apparatus (as for sterilizing) using superheated steam under high pressure
diurnal 1 a: recurring every day <~ tasks> b: having a daily cycle <~ tides> 2 a: of, relating to, or occurring in the daytime <the city’s ~ noises> b: active chiefly in the daytime <~ animals> c: opening during the day and closing at night <~ flowers> -- di.ur.nal.ly advdiurnal n (1600) 1 archaic: diary, daybook 2: journal 2a

isotropic : exhibiting properties (as velocity of light transmission) with the same values when measured along axes in all directions <an ~ crystal> -- isot.ro.py n

Rayleigh scattering : dispersion of electromagnetic radiation by particles that have a radius less than approximately 1/10 the wavelength of the radiation. The process has been named in honor of Lord Rayleigh, who in 1871 published a paper describing this phenomenon. The angle through which sunlight in the atmosphere is scattered by molecules of the constituent gases varies inversely
as the fourth power of the wavelength; hence, blue light, which is at the short
wavelength end of the visible spectrum, will be scattered much more strongly
than will the long wavelength red light. This results in the blue color of the sunlit
sky, since, in directions other than toward the Sun, the observer sees only
scattered light. The Rayleigh laws also predict the variation of the intensity of
scattered light with direction, one of the results being that there is complete
symmetry in the patterns of forward scattering and backward scattering from
single particles. They additionally predict the polarization of the scattered light.

**spec.trom.e.ter** 1: an instrument used for measuring wave lengths of light
spectra 2: any of various analytical instruments in which an emission (as of
particles or radiation) is dispersed according to some property (as mass or
energy) of the emission and the amount of dispersion is measured.

**spec.tro.pho.tom.e.ter**: a photometer for measuring the relative intensities of
the light in different parts of a spectrum

**col.li.mate**: to make (as light rays) parallel -- col.li.ma.tion n

**ther.mo.cou.ple**: a device for measuring temperature in which a pair of wires of
dissimilar metals (as copper and iron) are joined and the free ends of the wires
are connected to an instrument (as a voltmeter) that measures the difference in
potential created at the junction of the two metals

**ther.mo.pile**: an apparatus that consists of a number of thermocouples
combined so as to multiply the effect and is used for generating electric currents
or for determining intensities of radiation
## 8.4. SYSTEM CALCULATION

### 8.4.1. Location Data

<table>
<thead>
<tr>
<th>Location</th>
<th>Boston, MA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>42°</td>
</tr>
<tr>
<td>Longitude</td>
<td>71°</td>
</tr>
<tr>
<td>Elevation</td>
<td>15 ft</td>
</tr>
</tbody>
</table>

### 8.4.2. Climate Design Data

<table>
<thead>
<tr>
<th></th>
<th>°F</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Design Temp.</td>
<td>20</td>
<td>-6.67</td>
</tr>
<tr>
<td>W-Interior Design Temp.</td>
<td>72</td>
<td>22.22</td>
</tr>
<tr>
<td>S-Interior Design Temp.</td>
<td>68</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>°F</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Jan. Temp.</td>
<td>31.16</td>
<td>-0.47</td>
</tr>
<tr>
<td>Diurnal Swing</td>
<td>17</td>
<td>9.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Btu(\text{day}/\text{ft}^2)</th>
<th>Wh(\text{day}/\text{m}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Insolation</td>
<td>720</td>
<td>8178.2</td>
</tr>
<tr>
<td>Heating Degree Days 50°F</td>
<td>2416</td>
<td>1324</td>
</tr>
<tr>
<td>Heating Degree Days 65°F</td>
<td>5575</td>
<td>3079</td>
</tr>
<tr>
<td>Cooling Degree Days 50°F</td>
<td>2810</td>
<td>1543</td>
</tr>
<tr>
<td>Cooling Degree Days 65°F</td>
<td>695</td>
<td>368</td>
</tr>
</tbody>
</table>
8.4.3. Building Data

Overall Dimensions:

- width (east-west): 22 ft (6.71 m)
- length (north-south): 44 ft (13.41 m)
- height: 22 ft (6.71 m)

Total Volume: 21296 ft³ (603.04 m³)
Total Surface Area: 4840 ft² (449.65 m²)
Total Floor Area: 968 ft² (89.93 m²)

8.4.4. Surface Areas and Materials

### South Wall

**Overall Area (ft²):** 968

<table>
<thead>
<tr>
<th>Name</th>
<th>description</th>
<th>% of wall</th>
<th>Adj. Area (ft²)</th>
<th>U (Btu/h·ft²·°F)</th>
<th>UxA (Btu/h·°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mat3 (opaque)</td>
<td>wood framing</td>
<td>62</td>
<td>600.16</td>
<td>0.05</td>
<td>31.81</td>
</tr>
<tr>
<td>Mat4 (transparent)</td>
<td>double glazing</td>
<td>8</td>
<td>77.44</td>
<td>0.54</td>
<td>41.82</td>
</tr>
<tr>
<td>Mat1 (prop. element)</td>
<td>solar gain system</td>
<td>30</td>
<td>290.4</td>
<td>0.14</td>
<td>39.49</td>
</tr>
</tbody>
</table>

Total wall area (ft²): 600.16
Total transparent wall area (ft²): 77.44

**UxA**

- opaque: 41.82
- transparent: 41.82

**Overall transparent wall area (ft²):** 41.82

---

### West Wall

**Overall Area (ft²):** 484

<table>
<thead>
<tr>
<th>Name</th>
<th>description</th>
<th>% of wall</th>
<th>Adj. Area (ft²)</th>
<th>U (Btu/h·ft²·°F)</th>
<th>UxA (Btu/h·°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mat3 (opaque)</td>
<td>wood framing</td>
<td>94</td>
<td>454.96</td>
<td>0.05</td>
<td>24.11</td>
</tr>
<tr>
<td>Mat4 (transparent)</td>
<td>double glazing</td>
<td>6</td>
<td>29.04</td>
<td>0.54</td>
<td>15.68</td>
</tr>
</tbody>
</table>

Total wall area (ft²): 454.96
Total transparent wall area (ft²): 29.04

**UxA**

- opaque: 24.11
- transparent: 15.68

**Overall transparent wall area (ft²):** 24.11
<table>
<thead>
<tr>
<th>North Wall</th>
<th>Overall Area (ft²):</th>
<th>968</th>
<th>(m²):</th>
<th>89,93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>description</td>
<td>% of wall</td>
<td>adj. Area</td>
<td>U (Btu/h·f²·°F)</td>
</tr>
<tr>
<td>Mat3 (opaque)</td>
<td>wood framing</td>
<td>91</td>
<td>880,88</td>
<td>0,05</td>
</tr>
<tr>
<td>Mat4 (transparent)</td>
<td>double glazing</td>
<td>9</td>
<td>87,12</td>
<td>0,54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>East Wall</th>
<th>Overall Area (ft²):</th>
<th>484</th>
<th>(m²):</th>
<th>44,97</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>description</td>
<td>% of wall</td>
<td>adj. Area</td>
<td>U (Btu/h·f²·°F)</td>
</tr>
<tr>
<td>Mat3 (opaque)</td>
<td>wood framing</td>
<td>85</td>
<td>411,4</td>
<td>0,05</td>
</tr>
<tr>
<td>Mat4 (transparent)</td>
<td>double glazing</td>
<td>15</td>
<td>72,6</td>
<td>0,54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Roof</th>
<th>Overall Area (ft²):</th>
<th>968</th>
<th>(m²):</th>
<th>89,93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>description</td>
<td>% of wall</td>
<td>adj. Area</td>
<td>U (Btu/h·f²·°F)</td>
</tr>
<tr>
<td>Mat6 (opaque)</td>
<td>standard roof</td>
<td>100</td>
<td>968</td>
<td>0,03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Floor</th>
<th>Overall Area (ft²):</th>
<th>968</th>
<th>(m²):</th>
<th>89,93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>description</td>
<td>% of wall</td>
<td>adj. Area</td>
<td>U (Btu/h·f²·°F)</td>
</tr>
<tr>
<td>Mat7 (opaque)</td>
<td>standard floor</td>
<td>100</td>
<td>968</td>
<td>0,05</td>
</tr>
</tbody>
</table>

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8.4.5. Infiltration

Occupants: 4

\begin{align*}
\text{cf}^*\text{min/occupant:} & \quad 20 \\
\text{min/hr:} & \quad 60 \\
\text{cf/hr:} & \quad 4800
\end{align*}

Building Volume (ft$^3$): 21296

ACH due to occup.: 0,23

assumed ACH: 0,5 (due to leakage etc.)

Infiltration Load

<table>
<thead>
<tr>
<th>coeff.</th>
<th>* VOL $ft^3$</th>
<th>* ACH</th>
<th>* ADR</th>
<th>UxAinf $(Btu/hr*^\circ F)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,018</td>
<td>21296</td>
<td>0,5</td>
<td>1</td>
<td>191,66</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$191,66$</td>
</tr>
</tbody>
</table>

8.4.6. UxA Total

\begin{align*}
\text{South Wall} & \quad 113,12 \\
\text{West Wall} & \quad 39,79 \\
\text{North Wall} & \quad 93,73 \\
\text{East Wall} & \quad 61,01 \\
\text{Roof} & \quad 31,94 \\
\text{Floor} & \quad 48,8 \\
\text{Infiltration} & \quad 191,66
\end{align*}

UxA Total \quad 579,66

\begin{align*}
\text{UxA solar} & \quad 39,49 \\
\text{UxA Solar Gain system} & \quad 477,73 \\
\text{UxA non-south} & \quad 101,93 \\
\text{UxA south} & \quad 113,12 \\
\text{A solar} & \quad 290,4 \\
\text{Area Solar Gain System} & \quad 41,82
\end{align*}
### 8.4.7. Energy Gains and Balance Point Temperature

#### Solar Heat Gain

<table>
<thead>
<tr>
<th>VT</th>
<th>Btu/h*ft²</th>
<th>720 average daily total radiation transmitted through a vertical south facing single glazed window</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asouth</td>
<td>ft²</td>
<td>41.82</td>
</tr>
<tr>
<td>Area of south facing glass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Afloor</td>
<td>ft²</td>
<td>968</td>
</tr>
<tr>
<td>Floor Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>shading coefficient for south facing glass</td>
<td></td>
</tr>
<tr>
<td>Qs</td>
<td>Btu/h*ft²</td>
<td>1.3 ( \frac{VT\cdot Asouth\cdot SC}{24\cdot Afloor} )</td>
</tr>
<tr>
<td>Average Winter hourly Solar Gain</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Internal Heat Gain

<table>
<thead>
<tr>
<th>Occupants</th>
<th>Heat Gain/Occ. Btu/h</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>qp</td>
<td>Btu/h</td>
<td>450 Moderately active (ASHREA)</td>
</tr>
<tr>
<td>Equipment</td>
<td>Btu/h</td>
<td>1200</td>
</tr>
<tr>
<td>qe</td>
<td>Btu/h</td>
<td>1200</td>
</tr>
<tr>
<td>Lights</td>
<td>Btu/h</td>
<td>0</td>
</tr>
<tr>
<td>qI</td>
<td>Btu/h</td>
<td>0</td>
</tr>
<tr>
<td>T</td>
<td>hours of occupancy</td>
<td>8</td>
</tr>
<tr>
<td>Afloor</td>
<td>ft²</td>
<td>968</td>
</tr>
<tr>
<td>Floor Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qi</td>
<td>Btu/h*ft²</td>
<td>1.03 ( \frac{(qp+qe+qI)}{A}\cdot\frac{T}{24} )</td>
</tr>
<tr>
<td>total internal gain</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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### Qi total Energy Gain

<table>
<thead>
<tr>
<th></th>
<th>Total Energy Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_s$</td>
<td>Btu/h*ft$^2$</td>
</tr>
<tr>
<td>$Q_i$</td>
<td>Btu/h*ft$^2$</td>
</tr>
<tr>
<td>$Q_i$ Total</td>
<td>Btu/h*ft$^2$</td>
</tr>
</tbody>
</table>

### Balance Point Temperature

| $U_x A$ | Btu/h'*F      | 579.66 |
| $A_{floor}$ | ft$^2$ | 968   |
| $U_x A$ total | Btu/h*ft$^2$ | 0.6 $(U_x A/A_{floor})$ |

| $T_i$ | 'F | 68 |
| Average Interior Temp. |

| $Q_i$ Total | Btu/h*ft$^2$ | 2.33 |
| $T_b$ | 'F | 64.11 |
| Balance Point Temperature | $T_i-(Q_i$ Total/$U_x A$ total) |
### 8.4.8. Energy Balance

#### Yearly Space Heating Energy

<table>
<thead>
<tr>
<th>TLC (Btu/F)</th>
<th>13911.9 24 h *UxA total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD (°F)</td>
<td>5575 for location and 65°F Balance Point Temp.</td>
</tr>
<tr>
<td>k</td>
<td>0.8 Efficiency of Heating Equipment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Eh (Btu)</th>
<th>96945870 TLC*DD/k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly Space heating therms</td>
<td>969.49 Eh/100,000</td>
</tr>
<tr>
<td>kWh</td>
<td>28386 therms*29.3</td>
</tr>
</tbody>
</table>

#### Yearly Space Heating Energy based on Load Collector Ratio

<table>
<thead>
<tr>
<th>BLC (Btu/DD)</th>
<th>11197.01 24 * UA non-south</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check Buildings overall loss rate against value in MEEBS</td>
<td>11.57 BLC/ A floor</td>
</tr>
<tr>
<td>LCR (Btu/DD*ft²)</td>
<td>38.56 BLC/A solar</td>
</tr>
<tr>
<td>Solar Gain System</td>
<td>DG-C3 from MEEB Table C1 Appendix C</td>
</tr>
<tr>
<td>Code for Reference System</td>
<td></td>
</tr>
<tr>
<td>SSF</td>
<td>0.51 from MEEBS Table C3 Appendix C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Qaux (Btu)</th>
<th>30587434 (1-SSF)<em>BLC</em>DD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary Energy required</td>
<td></td>
</tr>
</tbody>
</table>

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### 8.4.9. Materials

#### Material 1  
**Description:** Proposed Facade Panel

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Width d (inch)</th>
<th>Conductivity k (Btu<em>in/ft²</em>hr*°F)</th>
<th>Conductance C (k/d)(Btu/ft²<em>hr</em>°F)</th>
<th>Resistance (k/d)(Btu/ft²<em>hr</em>°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Air (Fuller Moore)</td>
<td>0.35</td>
<td>7</td>
<td>20</td>
<td>0.17</td>
</tr>
<tr>
<td>Glass</td>
<td>0.25</td>
<td>0.16</td>
<td>0.16</td>
<td>0.25</td>
</tr>
<tr>
<td>Aerogel</td>
<td>1</td>
<td>7</td>
<td>28</td>
<td>0.04</td>
</tr>
<tr>
<td>Glass</td>
<td>0.25</td>
<td>7.56</td>
<td>7.56</td>
<td>0.13</td>
</tr>
<tr>
<td>Inside Air (Fuller Moore)</td>
<td>0.25</td>
<td>7</td>
<td>28</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Composite R-Value (ft²*hr*°F/Btu)**: 7.35

**U Value (1/∑R) (Btu/hr*ft²*°F):** 0.136

#### Material 2  
**Description:** Insulated Concrete Wall

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Width d (inch)</th>
<th>Conductivity k (Btu<em>in/ft²</em>hr*°F)</th>
<th>Conductance C (k/d)(Btu/ft²<em>hr</em>°F)</th>
<th>Resistance (k/d)(Btu/ft²<em>hr</em>°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Air (Fuller Moore)</td>
<td>2</td>
<td>0.16</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>Urethane Foam</td>
<td>3</td>
<td>12</td>
<td>4</td>
<td>12.5</td>
</tr>
<tr>
<td>Concrete</td>
<td>3</td>
<td>12</td>
<td>4</td>
<td>0.68</td>
</tr>
</tbody>
</table>

**Composite R-Value (ft²*hr*°F/Btu)**: 13.6

**U Value (1/∑R) (Btu/hr*ft²*°F):** 0.074

#### Material 3  
**Description:** Standard Wood Framing Wall, 2x6, 18 foot on Center

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Width d (inch)</th>
<th>Conductivity k (Btu<em>in/ft²</em>hr*°F)</th>
<th>Conductance C (k/d)(Btu/ft²<em>hr</em>°F)</th>
<th>Resistance (k/d)(Btu/ft²<em>hr</em>°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Air (Fuller Moore)</td>
<td>0.5</td>
<td>0.61</td>
<td>1.22</td>
<td>0.17</td>
</tr>
<tr>
<td>Wood bevel siding</td>
<td>0.5</td>
<td>0.38</td>
<td>0.76</td>
<td>1.32</td>
</tr>
<tr>
<td>Sheathing</td>
<td>5.5</td>
<td>0.32</td>
<td>0.06</td>
<td>14.61</td>
</tr>
<tr>
<td>3.5 Mineral Fibre</td>
<td>5.5</td>
<td>0.32</td>
<td>0.06</td>
<td>14.61</td>
</tr>
<tr>
<td>Framing 2x4</td>
<td>6</td>
<td>0.91</td>
<td>0.15</td>
<td>0.99</td>
</tr>
<tr>
<td>Gypsum Board</td>
<td>0.5</td>
<td>1.11</td>
<td>2.22</td>
<td>0.45</td>
</tr>
<tr>
<td>Inside Air (Fuller Moore)</td>
<td>0.25</td>
<td>7</td>
<td>28</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Composite R-Value (ft²*hr*°F/Btu)**: 19.03

**U Value (1/∑R) (Btu/hr*ft²*°F):** 0.053
### Material 4
**Description:** Double Glazed Window 1/4 inch airspace

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Width (d) (inch)</th>
<th>Conductivity k (Btu<em>in/ft²</em>hr²°F)</th>
<th>Conductance C (k/d)(Btu/ft²*hr²°F)</th>
<th>Resistance (k/d)(Btu/ft²*hr²°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Frame/ no coating</td>
<td>0.54</td>
<td>1.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AHREA Fundamentals</td>
<td>Composite R-Value (ft²*hr²°F/Btu)</td>
<td>1.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(m²*K/W)</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**U Value (1/ΣR)** (Btu/hr*ft²°F): 0.54

### Material 5
**Description:** Triple Glazed Window 1/4 inch airspace

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Width (d) (inch)</th>
<th>Conductivity k (Btu<em>in/ft²</em>hr²°F)</th>
<th>Conductance C (k/d)(Btu/ft²*hr²°F)</th>
<th>Resistance (k/d)(Btu/ft²*hr²°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Frame/ e=0.40</td>
<td>0.4</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AHREA Fundamentals</td>
<td>Composite R-Value (ft²*hr²°F/Btu)</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(m²*K/W)</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**U Value (1/ΣR)** (Btu/hr*ft²°F): 0.4

### Material 6
**Description:** Standard Roof Construction

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Width (d) (inch)</th>
<th>Conductivity k (Btu<em>in/ft²</em>hr²°F)</th>
<th>Conductance C (k/d)(Btu/ft²*hr²°F)</th>
<th>Resistance (k/d)(Btu/ft²*hr²°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Reference ASHRAE</td>
<td>30</td>
<td>5.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite R-Value (ft²*hr²°F/Btu)</td>
<td>(m²*K/W)</td>
<td>0.033</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**U Value (1/ΣR)** (Btu/hr*ft²°F): 0.033

### Material 7
**Description:** Standard Floor Construction

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Width (d) (inch)</th>
<th>Conductivity k (Btu<em>in/ft²</em>hr²°F)</th>
<th>Conductance C (k/d)(Btu/ft²*hr²°F)</th>
<th>Resistance (k/d)(Btu/ft²*hr²°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Reference ASHRAE</td>
<td>20</td>
<td>3.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite R-Value (ft²*hr²°F/Btu)</td>
<td>(m²*K/W)</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**U Value (1/ΣR)** (Btu/hr*ft²°F): 0.05
Section of Test Chamber

with sensor placement
Data #1.1
No Element

Temperature Inside, Outside, Buffer ambient

Data #1.2
No Element

Relative Humidity Inside, Outside, Buffer
Data #2.1

With Aerogel Element

Temperature Inside, Outside, Buffer

ambient

Data #2.2

With Aerogel Element

Temperature Inside/Outside Element

surface
Data #2.3

With Aerogel Element

Relative Humidity Inside, Buffer

Data #2.4

With Aerogel Element

Illuminance Inside/Outside Surface, Inside Ground
Data #3.1

With Aerogel Element

Temperature Inside, Outside, Buffer ambient

Data #3.2

With Aerogel Element

Temperature Inside/Outside Element surface
Data #3.3

With Aerogel Element

Relative Humidity Inside, Buffer

Data #3.4

With Aerogel Element

Illuminance Inside/Outside Surface, Inside Ground
Data #4.1

With Aerogel and PCM Element

Temperature Inside, Outside, Buffer ambient

Data #4.2

With Aerogel and PCM Element

Temperature Inside/Outside Element surface
Data #4.3
With Aerogel and PCM Element
Relative Humidity Inside, Buffer

Data #4.4
With Aerogel and PCM Element
Illuminance Inside/Outside Surface, Inside Ground
Data #5.1

With Aerogel and PCM Element

Temperature Inside, Outside, Buffer ambient

Data #5.2

With Aerogel and PCM Element

Temperature Inside/Outside Element surface
Data #5.3

With Aerogel and PCM Element

Relative Humidity Inside, Buffer

Data #5.4

With Aerogel and PCM Element

Illuminance Inside/Outside Surface, Inside Ground