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Identification of Building Applications for a Variable-Conductance Insulation

Thomas F. Potter ■ *National Renewable Energy Laboratory*
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1.0 Abstract

Recent experiments have confirmed the feasibility of controllable, reversible disabling of a vacuum insulation panel, which may result in the development of energy-efficient building envelope components. These components could extend the managed energy exchange through the building envelope from about 30% (typical with fenestration systems in commercial buildings), to as much as 90% of the gross wall and roof areas.

Further investigation will be required to optimize the thermal response and the magnitude of the R-value swing (from a difference between insulating and conducting insulating values of 4 to as high as a factor of 100). The potential for energy reduction by using the variable-conductance insulation in the building envelope is discussed, and other potential building applications are mentioned.

2.0 Introduction

2.1 Statement of the Problem

For the great majority of commercial, industrial and multi-family buildings in the U.S., an energy efficient building envelope is one which isolates the conditioned space from the environment. Some types of fenestration systems found in these buildings can be operated to manage the transfer of heat through the envelope when needed. This kind of thermal management by the operator of the building, in keeping with the naturally occurring variation in ambient thermal conditions, including solar, prompts the consideration of a different kind of thermal behavior in future buildings. These buildings could be, with improved control over the opaque part of the envelope, much more responsive to their thermal environment than is possible with current envelope components.

Recent work in our laboratory has demonstrated the technical feasibility of a steel insulation panel with variable conductivity (i.e., a variable conductance insulation [VCI]). We refer to the VCI in its insulating mode as being "enabled." Partial or complete "disabling" results in more thermal transfer. Figure 1 describes the repeatable thermal insulating performance demonstrated in an early hardware test. We have achieved performance of approximately a differential factor of 4 insulating value (R-value, hr-ft^2-F/Btu) with the first proof-of-concept prototype, and anticipate much higher differentials, with the intermediate goal a factor of 25. A factor of 25 would yield an R-value of the panel as a thermal insulator that is 25 times the R-value of the panel as a thermal conductor (e.g., R=0.5 to R=12.5, or R=0.2 to R=5.0).

Several mechanisms are being studied to defeat the passive insulating ("enabled") performance of a steel vacuum insulation we are developing and have described previously. That passive insulation relies on a thermos-like concept in which a vacuum is sandwiched between two metal sheets. An array of spacers prevents collapse of the steel envelope under atmospheric pressure loads. One "disabling" mechanism described by Bovenkerk (1965) is the flooding of the evacuated space with hydrogen. Variably heating a hydride provides the hydrogen; discontinuing the heating allows the hydrogen to reabsorb, re-establishing the insulating vacuum.

This report provides an initial, qualitative assessment of the energy savings potential of the VCI technology.

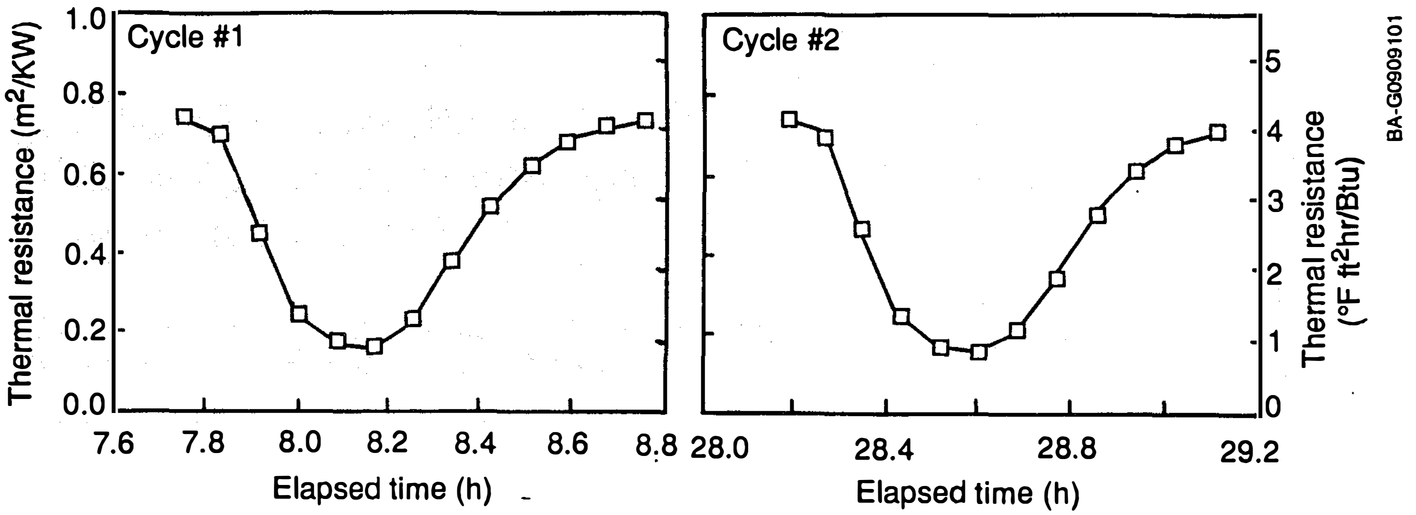

Figure 1. Thermal Response of Proof-of-Concept Variable Conductance Insulation Prototype. Without optimization of variables for large differences between "Enabled" and "Disabled" insulating values, a ratio of about 4 in thermal resistance was obtained and shown to be reproducible.

3.0 Analysis

3.1 Comparison of Possible Applications in Buildings

We compared the developmental attractiveness of a number of building application options for a VCI, and have presented a summary in Appendix A. The results of this comparison indicate that we should look most closely, initially, at the building envelope applications. Therefore, in the following section we more comprehensively examine these higher-priority potentials. This early work has been accomplished with program funding insufficient to support the use of energy simulation tools. We hope that these initial qualitative speculations will prompt detailed simulation to better identify optimal use of a VCI in buildings.

3.2 Potential for Variably Responsive Building Thermal Envelopes

3.2.1 Overview of Envelope Applications

Ambient temperature, wind, and solar radiation drive the energy exchanges through the envelope. In some cases (e.g., residences, strip shops and small offices) these exchanges dominate the total heating and cooling loads. In other instances, (e.g., large office buildings) they affect only the perimeter zones. Even there, because of the size of the building, the envelope-dominated area is substantial.

The most common solution for energy efficient walls and roofs, and one for which extensive simulations, test data, and in-field measurements exist, is to insulate to the maximum amount that can be cost-justified. As energy standards have become stricter, this approach has required more volume for increased insulation levels, to the point that common house-framing practices have been changed over the past 10 years to allow inclusion of more insulation in sidewalls.

Another approach, though less common, is to use massive thermal storage components in construction, such as concrete walls, floors, and roofs. This strategy is most effective where the daily and annual temperature excursions take place both above and below the desired internal temperature. The thermal lag, particularly in moderate climates with cooling loads, may give comfort equivalent to the high-insulation strategy, and may also result in low energy use.

Neeper (1982) suggests that one key objective of buildings efficiency research should be to "control the timing and quantity of accepted radiation, and control the transfer and storage of thermal energy." He further suggests that "enhanced heat transfer between the building envelope and storage, coupled with a diode effect, could double the efficiency of a passive (heating) system in cold climates." The controllable VCI systems being discussed here may have just the attributes desired, controlling the timing and quantity of solar radiation (as converted to envelope heating) and the thermal transfer from ambient to storage to occupied area. They may allow the building thermal envelope itself to act as a controllable diode between the building and the environmental thermal sources/sinks. In contrast to the "super-insulated" and "massive" strategies discussed previously, the VCI can be effective not only in envelope load-dominated buildings, but also in those with high internal loads. This is because a variable conductance envelope could release heat into and out of storage, and to the outside, when appropriate.

3.2.2. Previous Work on Variable Thermal Envelope Concepts

While the concept of responsiveness to the changing environment is well established, the potential for doing it automatically is relatively new. Typically, the management of solar gain and ventilation through current fenestration systems can affect up to 30% of the energy use of the building. With the new electrochromic and other "switchable" glazing technologies, this proportion could rise. Bartovics (1984) analyzes the energy effects of a variable transmissivity glazing for commercial buildings in several cities, showing major reductions in peak energy use in all climates, and in overall cooling energy use in cooling-dominated climates. Reilly et al. (1991) agree with Bartovics after a more comprehensive analysis, and added the important consideration of performance acceptance criteria.

The parallels between the continuing variable transmissivity (window) developments and the variable conductance work proposed in this paper are interesting. In both cases the control of variability depends on differences in climate, season, orientation, time of day, and building loads; in both cases there appears to be great promise for regulating the transfer and storage of solar gains, a characteristic we believe is important in addressing solar energy use in buildings. The VCI systems primarily take advantage of coupling to ambient air temperatures and radiant sinks, but also allow solar radiation to pass through the envelope, in the form of heat, when advantageous. The variable-transmittance glazings control only the beam and diffuse solar radiation.

Fine and McElroy (1990) examined concepts that are closer to the variable-conductance building envelope elements proposed here.

Their analysis used a computer simulation to estimate the savings from variable-resistance wall elements, and they found very small savings above that achieved by passive "super insulation" systems. While some potential was shown to exist for variable non-North wall conductances in residences, it was also far less than that shown for variable-transmissivity windows.

The characteristics of the VCI we are assuming may be different enough from those examined by Fine and McElroy to warrant further investigation. A new study could focus on three specific topics: first, a heating-load analysis would reveal the energy-efficiency potential arising from the improved access to solar gain and radiation losses through specific wall orientations. The improved access would derive from minimal thermal resistance of a VCI wall when the sun is shining on it (or when a heat sink is available), combined with negligible night losses. For residential buildings, the different assumptions required would be that (1) only those surfaces making a positive heating or cooling contribution would be "disabled" during the appropriate times, and (2) the structures would experience reasonably lower air exchange rates (i.e., 0.7 or fewer air changes per hour, compared with the 1.0 assumed in the previous study).

A second topic area would be roof cooling, and would involve a cooling-load analysis of the energy-saving potential of radiative roof cooling when appropriate. Although the main body of the population does not live within areas with low humidity, there appears to be both sufficient technical promise and sufficient regional energy use to warrant examination of that potential.

A third topic would be developed by conducting a total-load analysis of VCI systems within commercial buildings, which are significantly different than the residential profiles examined by Fine and McElroy. Commercial buildings have higher internal loads and larger unshaded window areas that differentially heat some orientations more than others; both effects could improve the payoff of a VCI wall system used in the opaque thermal shell.

3.3 Thermal Envelope—Walls

3.3.1 The Heating Potential of Variable

Neeper (1985) suggests that the average insolation on south-facing walls exceeds 50% of the heating load for residential buildings in most U.S. locations, even in those locations with cloudy skies during the heating season. His figure is reproduced as Figure 2. This finding indicates the potential benefit that could be gained by improving collection and use of the solar heating resource by and through broad areas of the thermal envelope.

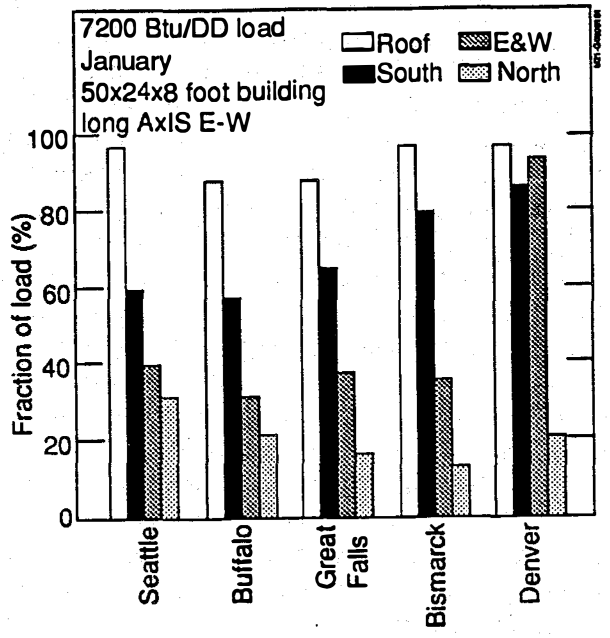

Figure 2. Ratio of Solar Energy Available to Heating Load for Various U.S. Climates, Assuming 1-day Thermal Storage Capacity, as an Indicator of Solar Space Heating Potential. Because these are particularly severe climates, it is reasonable to infer that insolation on the walls of a moderately insulated, skin-dominated building exceeds heating requirements in all Continental U.S. climates (Source: Neeper 1985).

Such a thermal envelope element, based on a variable conductance insulation, would have very high absorptance, very low resistance between the absorber and storage, and very low resistance between storage and the occupied space. A passive solar system with these characteristics has been extensively modeled and observed; it is the night-insulated water wall. Elements of a water wall that are similar to those of the VCI wall system, in addition to those mentioned above, include a large difference between its daytime and nighttime insulation level, and the use of glazing. According to Neeper (1987), some form of convection suppression is needed, whether it is called glazing or not; without some suppression device the external wall surface will not become hot enough in most cold climates to cause heat to flow to the inside. Such use of a "transparent insulation" has attracted a growing technical interest in Europe (Munding and Boy 1989). The other element, a large difference between day and night insulation levels, would, we assume, be provided by the VCI.

A practical consideration, of course, is how the other characteristics of the prospective VCI wall system would compare to those of the night-insulated water wall for market acceptance. Given the fact that night-insulated water walls, despite their excellent performance, have not achieved widespread acceptance in the consumer or building trade markets, we would prefer any VCI system to score better than the water wall apparently has on one or more of the acceptance factors such as First Cost, Aesthetics, Reliability, Daily Operator Requirements, Long-Term Maintenance Requirements, and Ease of Retrofit.

3.3.2 The Cooling Potential of Variable Conductance Walls

The cooling potential of walls is only a small fraction of the cooling potential of flat roofs, because of the reduced view factor to the radiant cooling "sink" of the sky. However, a combination of radiative cooling and nighttime convection cooling may be adequate to achieve superior overall performance, especially if the wall can function at other times in the other (i.e., insulating or heating) modes. A more complete discussion of the radiant cooling potential will be found in the Roof Cooling section that follows.

3.4 Thermal Envelope–Roofs

In U.S. residences, most roofs are thermally decoupled from the building by a buffer space (an unoccupied attic or a plenum), which can strongly dampen the thermal signal, require thermal transport into the occupied space, or both. However, commercial buildings often have flat roofs that are thermally coupled to the conditioned space. While in high-rise buildings these roofs account for only a small fraction of the envelope, they constitute a significant portion of the shell of buildings under 50,000 ft^2, which account for over half of the commercial floor space built each year.

3.4.1 The Heating Potential of Variable Conductance Roofs

Figure 3 is an initial concept sketch that shows the VCI envelope component in schematic form. In this case, excellent absorptance, minimal resistance to storage, and minimal resistance to the interior radiator would yield a warm ceiling panel radiatively coupled to the interior walls, floors, furnishings and occupants. The use of warm air for thermal comfort could be enhanced by the use of a ceiling fan to reduce stratification.

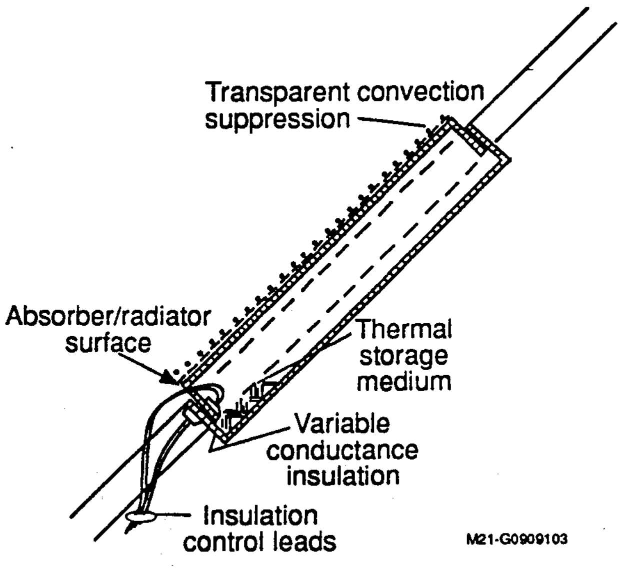

Figure 3. Conceptual Sketch of a Variable Conductance Insulation Roof Panel. Placement here is that appropriate for a Heating/Cooling panel, rather than for a complete roof area replacement.

3.4.2 The Cooling Potential of Variable Conductance Roofs

The radiative cooling resource is far less abundant and far less well known, and has received relatively little attention by the research community (Neeper 1985). The simplest observation about the radiative cooling resource is that, if it is effective in a particular location, radiation to the sky is also cooling the ground near the building. This will result in a large mass of cool air that could perhaps more easily be drawn into the structure for cooling, rather than building a separate radiant cooling system; such a system could require heat dissipators on the roof, a method for storing the cooler fluid, and another method to expose it to the occupied space. While the air-moving solution is a legitimate one, there are humidity issues and system synergisms that encourage a roof-dissipator approach in many locations, and we will continue here with that systems-oriented line of discussion.

The net thermal radiation at commonly achieved roof radiator temperatures could amount to 50 to 200 Btus per night per square foot of rooftop radiator under clear skies in humid climates, and perhaps 50% more in dry climates (Clark 1989). This does not compare well to design cooling loads of perhaps 100 Btus per hour per square foot of floor space in a building, but experience with operating systems has been good. Locating the cooling panel in a residential ceiling couples the cooling need with the cooling resource, and may add to comfort by changing the mean radiant temperature directly and indirectly.

The practical radiative cooling potential from the roof may best be bounded by performance of the roof pond; it appears to be an excellent passive cooling performer for many of the same reasons its vertical counterpart, the water wall, does well in a heating mode. Significant progress in understanding methods for tapping the cooling resource accessible to roofs was made by Hay and Yellott (1969) with their work on roof ponds with movable insulation. Work continues on the roof pond concept, with water sprays providing additional, evaporative cooling in many locations [1], and other integrated concepts also being developed (Balk 1988). As reviewed by Martin (1989), one of the major factors impeding wide-scale development of roof ponds, despite their known good thermal performance, is their current requirement for sliding thermal insulation panels.

Martin (1989) combined dry- and wet-bulb temperatures to assess the national potential for radiant cooling. Figure 4 reproduces the contour map for July, which shows a broad range of locations with good potential performance. VCI roof panels could tap that potential, improving on the performance of the current movable insulation panels on roof ponds, which have proven to be "expensive and mechanically unreliable" (Clark 1989).

3.5 Energy Simulations

Several DOE-2.1D parametric runs were performed on a light manufacturing building located in Connecticut. The software currently allows adjustments of wall and roof R-values according to the outside air temperature. The simulations were

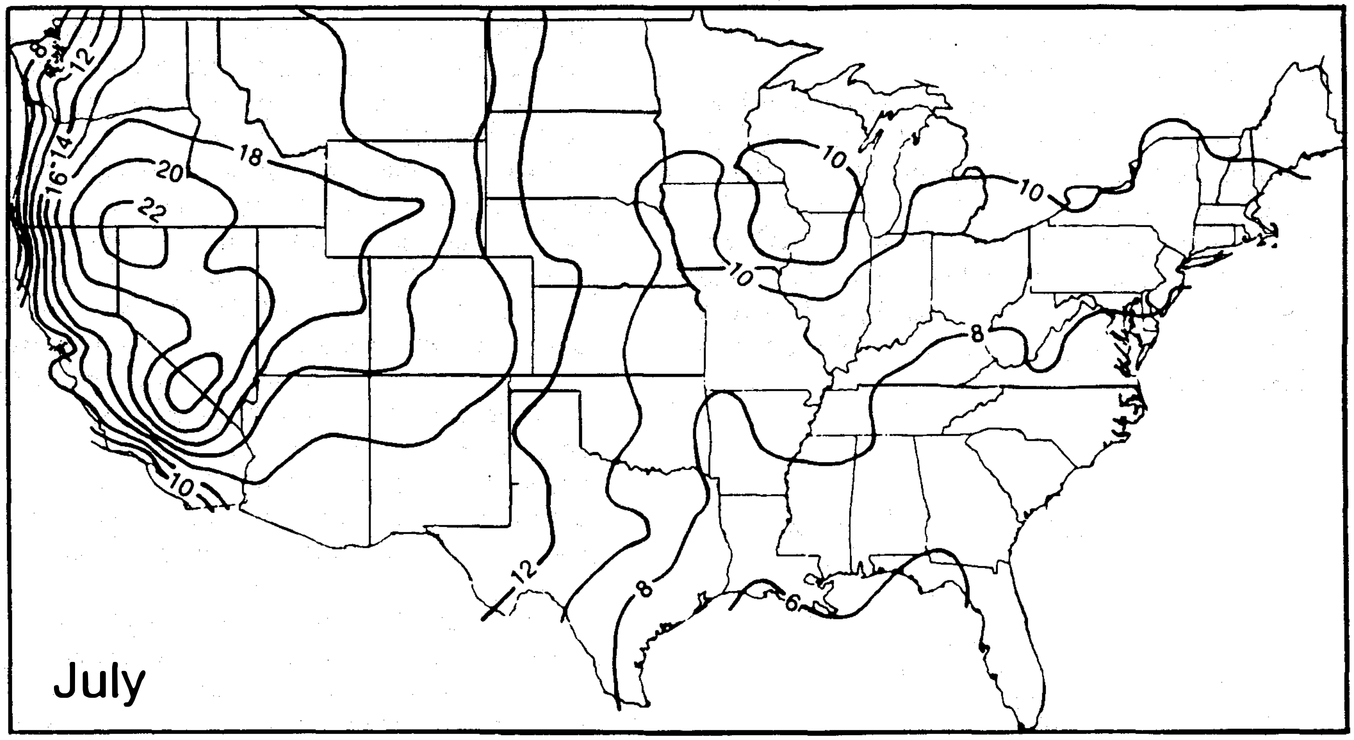

Figure 4. Average Monthly Sky Temperature Depression, dTsky = Tair - Tsky, as an indicator of radiative cooling potential. Annual sky temperature depression statistics show that sites such as Fresno, characterized by low humidity and clear summer skies, could be excellent for radiative cooling. Sites more like Miami, with high humidity and cloud cover, would probably be poor candidates (Source: Martin and Berdahl 1984).

undertaken with panels that could change their R-value from 0.5 to 13.0, and that were located in walls. A scatter plot of energy savings and energy increases was obtained, according to the outside air temperature threshold used to "enable" the panels. Building orientation (and therefore the amount of solar radiation received by the wall panels) had a strong effect on results.

This preliminary computer analysis showed that the VCI panels do not perform well when scheduled in accordance with the outside air temperature.

A better predictor of their performance would have to incorporate (a) outside air temperature plus solar radiation received on panel surface, (b) outside air temperature and temperature of the outer skin of the panel, or (c) perhaps only the temperature of the outer skin of the panel, when the panel does not incorporate any substantial mass.

To simulate such strategies, modifications will need to be made to any of the currently available energy analysis tools.

3.6 Conclusions on the Application to Walls and Roofs

There appear to be three ways to manage thermal transfer through the building envelope:

(1) High-Insulation. Passive thermal insulation is installed between the variable thermal signal and the steady-state interior; the thermal consequence is that the exterior thermal signal is greatly attenuated and slightly delayed on its way to the interior. This approach serves to isolate the interior from the exterior, rejecting any potential for benefit from the outside. The interior is then dealt with according to auxiliary heating, ventilating and cooling equipment practice, with the reduced efficiency deriving from central control imprecision, losses associated with delivery from a distant heat or cold source, and the discomfort of improper design/adjustment of current distribution terminals. Transient modifications of the high-insulation system

according to varying exterior conditions are not usually possible.

(2) High-Mass: thermal mass is installed between the variable thermal signal and the steady-state interior; the thermal consequence is that the exterior thermal signal is greatly delayed and slightly attenuated. Practically speaking, this approach puts the thermal signal sufficiently off-cycle that with proper choice of mass the heat is usable inside at a better time than it was available outside. Transient modifications to the high-mass system according to varying exterior conditions are not usually possible.

(3) Variable Conductance Insulation: a small amount of thermal mass may be installed between the variable thermal signal and the steady-state interior, and further, between variable conductance insulation panels. The thermal consequence is that the exterior thermal signal can be passed on with minimal delay and very slight attenuation. Practically, this approach transmits the exterior thermal signal on about its original cycle, if desired, or stores it for later transmittal to the interior, or rejects it as unusable at a particular time. Transient modifications to the VCI system according to varying exterior conditions comprise the normal operating conditions. This flexibility of control should nicely fit the complex situation of highly variable outside conditions and somewhat variable inside requirements common in most buildings. In addition to calculable savings in auxiliary energy use, the VCI systems may provide the additional benefit of improved Mean Radiant Temperature near the occupant, the improved comfort of which could lead to further savings. Table 1 describes first thoughts on a possible operations-logic system for using a VCI system.

To better define the relation of the VCI wall or roof system components to performance, we arrayed them against the locations they might occupy. The result of this simple comparison is Table 2, which appears to indicate that the highest payoff would be for south-tilted VCI systems, whether on wall or roof. These can more easily pay for themselves (if the incremental cost is not too high) by performing thermal duties both summer and winter. An integrated-storage wall or roof system facing south,in which the VCI serves as a space cooler and space/water heater, as well as other envelope functions, would be an interesting example of such a relatively high-value component.

3.6.1 Initial Identification of High-Value Envelope System Applications: Operating Characteristics

Several building types can benefit from the use of a variable conductance envelope. The following discussion addresses the operating conditions under which such panels could be effective in saving energy.

Light Manufacturing (electronics, plastics, assembly, etc.)

High exothermic processes create cooling loads during operating hours in these buildings even during late fall/early winter/early spring. Yet at night there are heating requirements.

Strategy: low R-values during occupied hours, and high R-values during unoccupied hours.

Strip Shopping

These buildings are often built "on speculation" (i.e., unknown tenants) and contain a mix of retail stores. Lighting loads are typically high, because many retailers use incandescent lamps for display lighting. Some, such as coffee shops, also generate significant process heat loads. Cooling loads are fairly high over much of the year, so low-R walls and roofs are appropriate during the day, when the outside air temperature is below 70 degrees F and the surface is shaded. During mornings and at night, and during cold spells, heating may be necessary.

Strategy: Variable R-values to allow low-R envelopes for those uses (and during those periods) in which excess heat is generated, with high-R performance accessible when needed.

Shopping Centers

These building clusters have high internal gains. The cooling load on the upper floors is high because of direct gain and the multistory open spaces that allow extensive air movement in the vertical plane. Very often the roof insulation impedes desirable heat transfer to the ambient and "traps" heat during cooling periods. Heating loads are experienced during the winter.

Strategy: low-R makes sense during cooling hours when outside air temperatures are lower than

Table 1. Operating Modes Proposed for a Prototype Variable Conductance Insulation Wall Heating/Cooling System. (EN = Enable, DIS = Disable, AMB = Ambient)

Temperature		Heating				Cooling			
		Outer		Inner		Outer		Inner	
		EN	DIS	EN	DIS	EN	DIS	EN	DIS
AMB	MASS								
0	0	X		X			X		X
0	70	X		X			X		X
0	100	X			X		X	X	
70	0		X	X		X			X
70	70	X		X			X		X
70	100	X			X		X	X	
100	0		X	X		X			X
100	70		X		X	X			X
100	100		X		X	X		X	

Table 2. Comparison of Performance Potential of Alternative VCI Placements

(radiative space cooling = c [only where and when humidity is low], space heating = h, water heating = w)

	horiz	vertN	TILT45N	vertS	TILT45S
roof	c		cd		c,h
wall		c	c	c,h	c,h
collector	c,w	c	c	c,h,w	c,h,w

interior air temperatures, as is often the case, in temperate climates, near shaded walls. High-R is used in winter or during cooling season periods with high ambient temperatures, especially on solar-irradiated surfaces.

Apartment Buildings

During swing seasons and also during the heating season in mild climates, an apartment may overheat from solar gain, and remain too warm even after sunset.

Strategy: A wall that is shaded during the day can be maintained with a low-R performance for cooling load reduction. Walls with southerly orientations can benefit from a low-R/high-R strategy, with control required more than once during a 24-hour period. During early morning, high-R avoids overheating on the east from solar gain, and during the mid-day it protects against high ambient temperatures. In the evening, low-R promotes cooling, and at night high-R protects against too-low ambient temperatures.

Office Buildings

Overheating in office buildings reduces worker productivity. Much of the heat gain is generated by lighting and office equipment, and is usually extracted through the use of mechanical cooling.

Temperatures are maintained in the 70 degrees F to 76 degrees F range, so low-R walls can be effective when a cooling load exists and when the outside air temperature is below 70 degrees F (or a minimum of 5 degrees F below office air temperature). This first cooling situation occurs occasionally during swing seasons, but that may not offer sufficient justification for a panel control component in many climates. However, office applications exist in which: (1) extended periods of cooling loads coincide with cool ambient temperatures, and (2) increased night ventilation is either impossible or undesirable (typically because of problems with control or humidity):

- In mild climates, especially Southern California and coastal locations.
- In moderate climates that experience high solar gain during the heating season, for example, in a 4,000-6,000 degree-day band across the United States. High solar gains could be caused by a combination of southerly orientation and high-transmission glazing, especially when the glazing covers a relatively large envelope area (e.g., above 25% of the wall area).
- In mild, moderate, and cold climates with especially high internal loads (e.g., desktop publishing and data processing).

The second cooling situation may arise when mass that could be associated with the variable conductance insulation is passively "charged" during the off-cooling-peak hours, and "discharged" to offset peak cooling loads.

4.0 Promising Areas for Further Analysis

We have provided information on this new VCI concept to encourage further investigation of VCI systems in buildings. More detailed analysis is clearly needed. Neeper's comments are relevant to this requirement for improved analysis: "Although it is easy to picture progress as the development of hardware, in fact the common base for progress is a continuing systems analysis that initiates research by evaluating ideas, that guides research by providing performance estimates, and that applies the products of research by providing design rules" (Neeper 1985). Such analysis could focus on several topics:

(1) Quantitative studies are needed to separate those areas of VCI speculation that have little potential for energy savings from the smaller number of them that could result in a significant contribution in buildings.

(2) Optimization is needed of control and thermal storage strategies. This will assist in the design of improved VCI buildings systems and drive the development of better thermal storage materials.

(3) Methods must be identified and developed to incorporate the VCI into standard new building construction and building retrofit materials and construction practices.

5.0 Conclusions

An initial qualitative examination of applications possible using a variable conductance insulation concept reveals significant opportunities for major impacts on building energy use. These opportunities are especially noteworthy in the design and operation of thermal envelope components that are responsive to the changing environment. Future buildings work should take into account these new ways to improve the efficiency of interaction between the built environment and the natural environment.

6.0 Acknowledgments

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7.0 Endnotes

7.1 Personal Communications

(1) J. Douglas Balcolm, NREL. March 1992.

(2) Craig Christensen, NREL. February 1992.

(3) K. Thomas Feldman, KTF Research. March 1992.

(4) Yogi Goswami, University of Florida. February 1992.

(5) Byron Stafford, NREL. March 1992.

7.2 Other Notes

While thermal energy storage (TES) is not itself a part of the VCI operating system, we think that various VCI systems will often incorporate TES. A moderate amount of TES may be advantageous in several ways; it may:

- ease the requirements for VCI operations controller sensitivity
- introduce operating flexibility into the system by allowing relatively unobstructed thermal input on one side of the panel, but measured output on the other side, (e.g., the interior VCI cooling panel may be only partially "disabled" to avoid condensation)
- delay and store thermal input to better match occupant needs (including comfort, energy use, and energy peaks) with outside temperature or radiant sources/sinks.

The question of TES is, however, a complex one. Definitive statements must await much more comprehensive analysis of the its effects, alone and synergistically, within a VCI system.

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Appendix A. Comparison of Building Applications of a VCI System

Application	Site	dt	Dwell	Svgs/Unit	Units	Impact
roof	ambient	lo	lo	mod	v hi	hi mod
walls	ambient	lo	lo	mod	v hi	hi mod
GSHP	earth	lo	lo	mod	mod	mod
furnace	flue	mod	lo	lo mod	hi mod	mod
dwh/gas	flue	mod	lo	lo mod	hi mod	mod
dwh/elec	TES	hi	hi	mod	lo mod	mod
TES	ducts	lo	mod	lo mod	lo mod	lo mod
sdwh	TES	mod	lo	lo	lo mod	lo mod
PV panels	TES	mod	lo	lo	v lo	low

KEY

Site: location of the variable conductance insulation

dt: maximum temperature difference

Dwell: time at dt

Units: size of potential market

GSHP: ground source heat pump

dwh: domestic water heater

TES: thermal energy storage

sdwh: solar domestic water heater

PV: photovoltaic