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Thermal Comfort Strategies: A Report on Cellulose Insulation

by

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The U.S. Army maintains 979 million sq ft of space in 171,647 buildings worldwide. Thermal energy costs approximately \$350 million per year, of which an estimated \$84 million could be saved with simple building envelope construction techniques. Past design and construction standards depended on infiltration at weak points in the building envelope to bring fresh air inside. Extensive sealing and caulking followed by an introduction of outside air seems, at first, a contradiction. However, the combination of carefully sealing the building envelope and improving the ventilation system improves comfort, saves energy, controls moisture, increases indoor air quality, and, in general, increases user satisfaction. Thermal comfort is an important aspect of occupant comfort and subsequent productivity. With 1,334,352 Army employees and a \$20 billion payroll, even a

modest 5 percent increase in productivity could mean an annual savings of \$1 billion.

This report presents thermal comfort strategies relating to the use of cellulose insulation from both human comfort and technical perspectives. The report discusses some general concepts on human comfort, and briefly describes desirable thermal insulation properties and the attainment of these properties using cellulosic materials. Techniques for the selection and installation of cellulose insulation are described. The report also discusses technical issues involved in general thermal comfort strategies, including: infiltration, thickness effects, settling, and blower door testing. Finally, technical standards are referenced for the selection and installation of cellulose-based insulation materials.

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Foreword

This study was conducted for the Directorate of Military Programs (CEMP), Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT45, "Energy and Energy Conservation"; Work Unit FL-X66, "Energy Efficient Envelope Strategies - 1996." The technical monitor was Joe McCarty, CEMP-ET.

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Contents

SF 298	1
Foreword	2
1 Introduction	5
Background	5
Objectives	5
Approach	5
Scope	6
Mode of Technology Transfer	6
2 Thermal Comfort	7
Comfort	7
Energy Conservation	9
Moisture Control	9
Indoor Air Quality	10
Air Pressure	11
Ventilation	12
3 Thermal Insulation	13
Desirable Properties of Insulation	13
Cellulose Fiber Insulation	14
Technique and Location Selection	15
4 Technical Issues	17
Infiltration	17
Convection	19
Conductivity	20
Thickness Effects	23
Settling	23
Blower Door Testing	23
Environmental Boundaries	24
Backdrafting	24
Moisture and Vapor Barriers	25
Thermography	26
5 Summary	27
Standards and References	28
Distribution	

1 Introduction

Background

The U.S. Army maintains 979 million sq ft of space in 171,647 buildings worldwide. Thermal energy use costs approximately \$350 million per year, of which an estimated \$84 million could be saved with simple building envelope construction techniques. Past design and construction standards depended on infiltration at weak points in the building envelope to bring fresh air inside. The laborious tasks of extensive sealing and caulking followed by an introduction of outside air seems, at first, a contradiction. However, the combination of carefully sealing the building envelope and improving the ventilation system improves comfort, saves energy, controls moisture, increases indoor air quality, and, in general, increases user satisfaction. Thermal comfort is an important aspect of occupant comfort and subsequent productivity. With 1,334,352 Army employees and a \$20 billion payroll, even a modest 5 percent increase in productivity could mean an annual savings of \$1 billion (USACPW 1995).

Objectives

The objective of this report is to provide a source of information on cellulose insulation types, installation techniques and properties, and the use of this information on thermal comfort strategies for new and retrofit construction projects.

Approach

Research and development for this report encompassed the following:

- Research of current publications on cellulose insulating materials and computer based building design tools.
- Internet download of publicly financed research on thermal comfort as it pertains to cellulosic building material systems.
- Research into ASHRAE standards and design fundamentals regarding thermal comfort.

- Integration of the above sources of information into a comprehensive document.

Scope

This report presents a broad background of information on the current state of cellulose insulating technologies. It also presents some preliminary design issues that should be addressed in the analysis of thermal comfort. It can also serve as a source of information for further thermal comfort issues. The issues examined in this report include:

- thermal comfort concepts
- thermal insulation basics
 - cellulose insulation technologies
 - cellulose installation options
- technical issues.

It should be recognized that building design in general is context sensitive. Unless multiple buildings are being built in the same geographic region, on the same site, and with the same orientation, an analysis should be conducted for each individual building design.

Mode of Technology Transfer

Information from this study will be published in the *Public Works Digest* and disseminated through Energy Awareness and Energy Managers Conference seminars.

2 Thermal Comfort

Comfort

Tight envelope construction prevents leaky buildings that are drafty and uncomfortable. Preventing leaks improves comfort, user satisfaction, and subsequent user productivity. However, unlike quantifying energy, quantifying comfort and user productivity is very complex. The American Society of Heating, Ventilating and Air-Conditioning Engineers (ASHRAE) has conducted extensive research regarding building occupant responses to interior environmental conditions. To determine human responses to fluctuating air velocities, Fanger and Christianson (1985) established a baseline for measuring the mean air velocity that causes 15 percent of the population to report feeling a draft (Figure 1).

Drafts can lead to increased temperature stratification (or gradient) within occupied spaces. If the gradient is sufficiently large, a localized warm discomfort can occur near the head area and a cold discomfort can occur at the feet. To quantify the influence on thermal comfort resulting from vertical air temperature differences, Oleson, Scholer, and Fanger (1979) designed an experiment whereby subjects were exposed to variations in temperature gradients while seated in a thermally neutral space. Thermal neutrality was achieved by allowing the subject to change the temperature level in the test room whenever they desired. The subjects reported on their perceived thermal sensation (Figure 2), illustrating that as the temperature differential increased, occupant satisfaction decreased.

Marginally insulated envelopes can also have excessively high or low surface temperatures, which leads to an uncomfortable mean radiant temperature for the interior space. The mean radiant temperature is a measurement of the radiant energy lost or gained by an occupant through exchange with the immediate environment. Even if the surrounding *air* temperature is comfortable, the occupant can lose or gain uncomfortable amounts of energy through radiant exchange with hot or cold building surfaces. Figure 3 shows that as the mean radiant temperature of the conditioned space decreases, air temperature must be increased to compensate for occupant radiative heat losses (the inverse would also be true) (ASHRAE 1993).

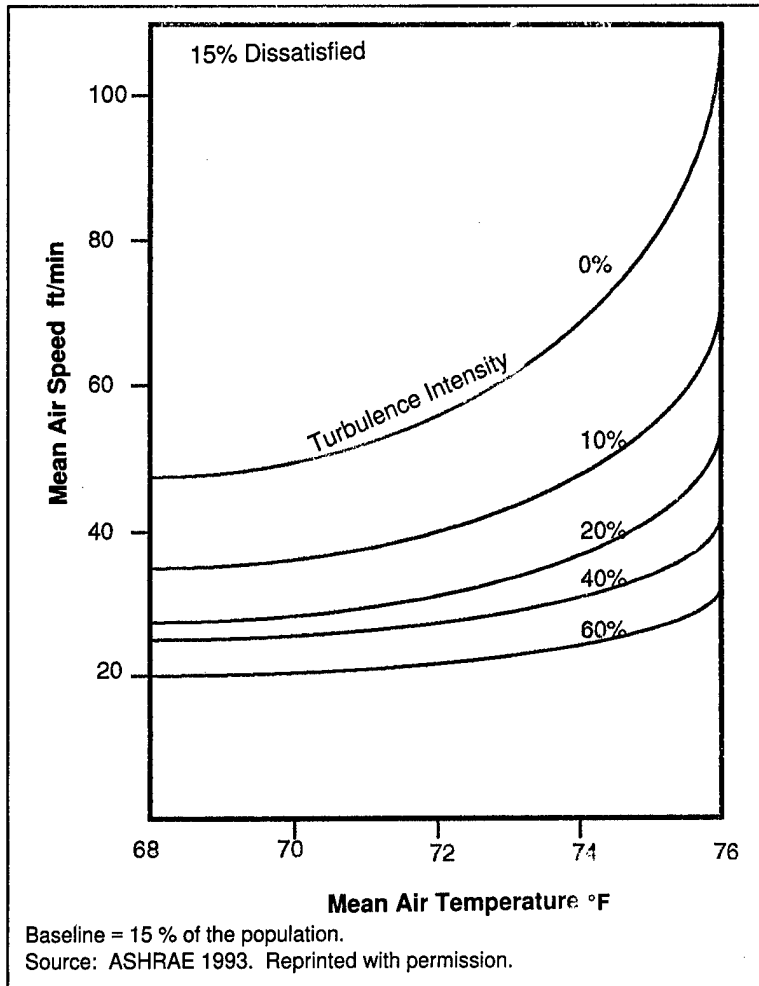


Figure 1. User satisfaction as a function of draft conditions.

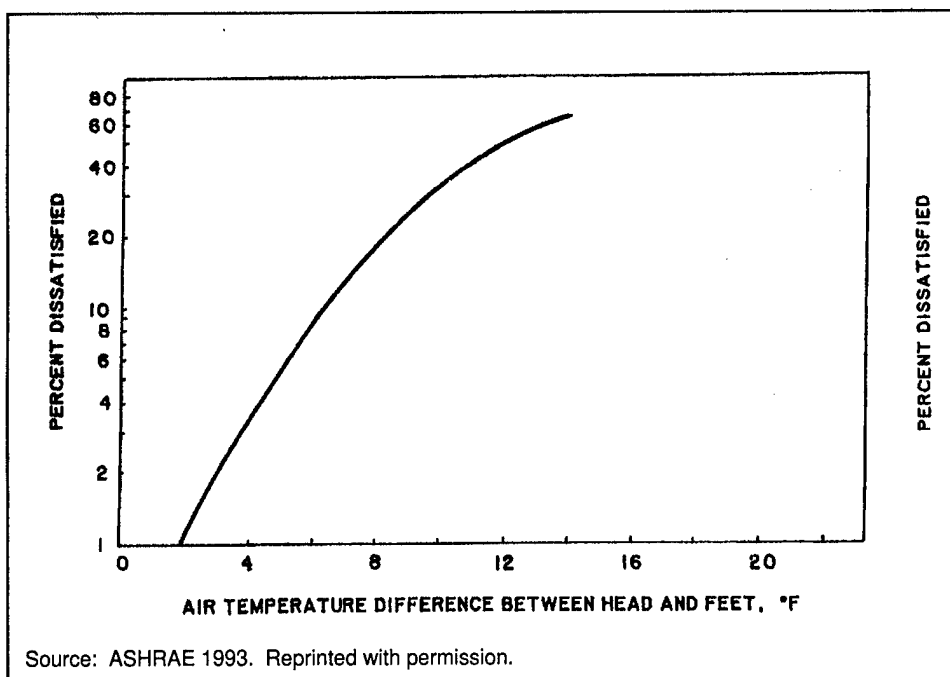


Figure 2. User satisfaction as a function of air temperature stratification.

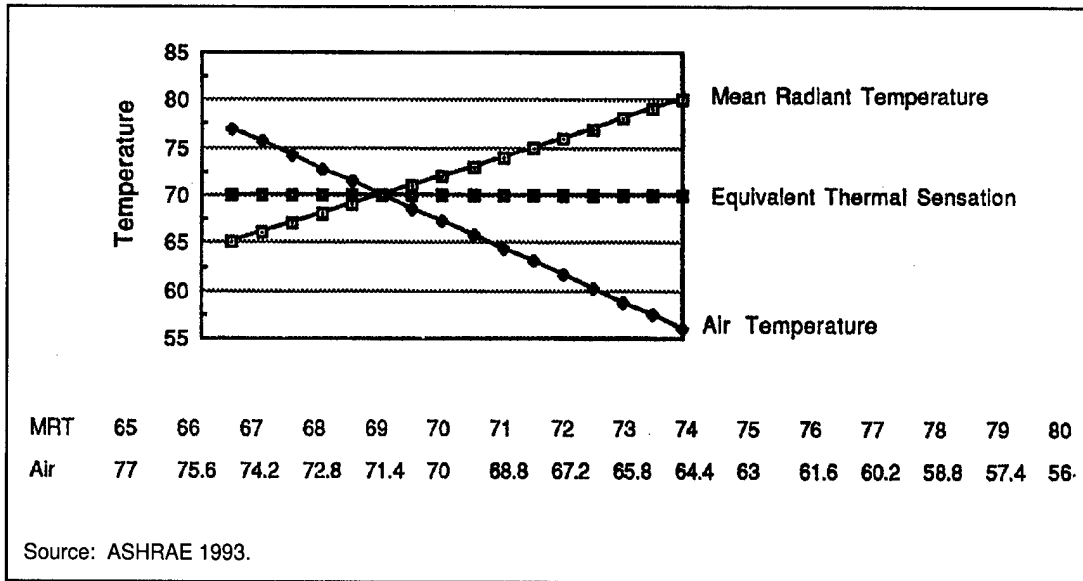


Figure 3. Radiant temperature implications.

The preceding studies indicate that the management of infiltration and improved insulation in the design of a building envelope system can lead to better thermal comfort and more satisfied occupants. The hypothesis that increased comfort leads to a more productive work force has yet to be proven, although it appears to be a logical supposition, and is accepted by most people as self evident. While the economics of energy conservation opportunities are analyzed typically on energy saving criteria alone, the human comfort benefits should also be considered.

Energy Conservation

Sealing the building envelope is one of the most cost-effective ways to save energy in buildings. In residential construction, using typical construction methods that do not incorporate careful air-sealing techniques, simple air leakage can account for about one-third of the heating and cooling costs incurred (ESN 1995). Energy savings from sealing air leaks can therefore amount to substantial cost savings. "Once you put a lot of insulation in the envelope, air sealing is about the only thing left," said Bill Reed, a builder of affordable homes in Portland, OR (ESN 1995).

Moisture Control

Reducing the amount of indoor air leakage also reduces the potential for building decay. As air leaks through the building envelope, it can carry large amounts of water vapor. If temperature differentials exist such that the dewpoint is reached within the envelope assembly, the vapor will condense to liquid on cool component

surfaces, supporting the growth of decay organisms (insects, fungi, etc.), and ruining insulation or structural components. Water can migrate into envelopes by diffusion through envelope materials or through an air and water vapor mixture leaking into the wall. The vapor leakage carries much more moisture into the building envelope cavity than diffusion through envelope materials. Vapor retarders such as 4-mil plastic, low-permeable paint, and the facing on insulation can block diffusion, but they have little effect on air leakage through holes and cracks. Reducing indoor air leaks is a key strategy in extending the life of a building.

Indoor Air Quality

Some indoor air pollution problems actually begin outside. Tight construction techniques keep out some of these pollutants, such as radon gas, which occurs naturally in the soil. A well-sealed floor system is the first line of defense against radon, and a prerequisite for other measures, such as under floor ventilation systems. Similarly, the construction of a tight envelope can act as a defense mechanism against some potentially hazardous materials used in the building structure, such as some forms of foam insulation or treated wood. Tight construction can also prevent growth in the envelope system of molds and fungi, contributors to poor indoor air quality.

Poor indoor air quality can also be caused by an abundance of harmful materials used inside the structure. The phenomenon of "sick building" syndrome is caused, in part, by the "outgassing" of chemical compounds used in the manufacture and installation of a myriad of products. One of the first steps in improving indoor air quality is to ensure that controlled, adequate, and clean amounts of fresh air are introduced into the building. Fresh air intake locations should therefore avoid drives and loading docks, exhaust air ducts, garbage disposal locations, and employee smoking areas. If needed, a filtration system should be installed to remove contaminants (Barnett 1995). The natural infiltration of outside air through a leaky building envelope is by no means "controlled."

Rather than concentrating efforts on additional equipment to replace air that has been contaminated by interior products, simply not introducing these pollutant-emitting products in the first place may prove to be a more direct and less expensive way of achieving fresh air. The building industry is in the process of analyzing building products and quantifying their environmental impact. The National Park Service, the American Institute of Architects, and others have developed databases that address some of these issues. Although the quantification of the environmental impact of building products is still an emerging field of study, substantial inroads

have been made. One of the biggest hurdles that needs to be overcome is the dissemination of information and the education of architects, engineers and designers regarding where to get the information and how to use and decipher it to make informed building design decisions. Only when the people involved with the building design are educated to these issues will they be addressed appropriately.

Air Pressure

Improving comfort, saving energy, controlling moisture, and increasing the indoor air quality are all related to the movement of air into and out of a building. Air movement through a building is caused by a differential in air pressure across the building envelope. When the air pressure inside a structure is greater than it is outside, there is positive pressure indoors. When the pressure inside is less than it is outside, there is negative pressure indoors. Positive interior pressures force the interior air out through cracks in the building envelope, while negative interior pressures allow exterior air to migrate in through the envelope. Pressure is seldom uniform throughout the entire building. It can be strong in some areas, weak in others, or positive in some rooms and negative in others, but the air always moves from the greater pressure to the lesser in an effort to maintain equilibrium. Air pressure differentials in and around buildings can be mechanically induced by furnace or exhaust fans, or naturally induced by wind or indoor/outdoor temperature differences (the "stack effect").

The stack effect occurs because of the density difference between warm and cold air. During the winter, warm (and lighter) interior air will rise within the building, and if offered an exterior "escape route" will be replaced by heavy outdoor cold air through cracks in the lower portion of the building envelope. This situation results in a positive pressure within the upper portions of the building and a negative pressure within the lower portions. During the summer, the flows and pressures are reversed, but are generally lessened because of the smaller indoor/outdoor temperature difference. In general, the indoor/outdoor pressure differential anywhere on the building envelope depends on the sum of all the local mechanical and natural pressure differences as well as any nearby openings in the envelope.

It is best to control air exchange mechanically through a building envelope rather than just allowing it to occur naturally. Most houses have devices that pull air out of a building, which can create negative internal pressure. These devices include exhaust fans, range hoods, clothes dryers, woodstoves, fireplaces, combustion furnaces, and water heaters. If makeup air is not supplied through a controlled

system, it will be made up through leaks in the envelope. Water vapor contained in uncontrolled air leaking either way through the envelope can lead to internal decay.

Ventilation

Adequate ventilation is crucial because Americans typically spend up to 80 percent of their day indoors (Barnett 1995); however, "natural" air leakage is not ventilation. As mentioned in the section on air pressure, the two natural forces that drive air leakage are wind and the stack effect. Wind creates positive and negative pressure differentials on different surfaces of a building. These pressure differentials then cause air leakage both into and out of the building envelope. The wind is unpredictable, of course, so wind-induced leakage is also unpredictable. The outdoor temperatures that drive the stack effect are also unpredictable. Mechanically induced leakage depends on the configuration of appliances and fans running and, to some extent, on outdoor conditions, so it too is unpredictable. Therefore, the previous practice of leaving a structure intentionally leaky so it can "breathe naturally" is not a reliable or predictable ventilation technique.

More buildings now contain automatic ventilation systems to control this pressure exchange. The simplest systems, and the most popular, use an exhaust fan to expel stale indoor air. This places a negative pressure within the house that draws fresh air in through controlled vents. Automatically controlled, mechanical ventilation is essential for a tightly constructed structure. Modern, low-volume ventilation systems circulate from 80 to 200 cu ft of air per minute through the building. Low-volume ventilation systems work best in tightly constructed conditions where airflow can be controlled and predicted. Analogous to electricity, air flow follows the path of least resistance, be it through a hole in the wall, or through a controlled ventilation system. In a tight structure, that path is from the fresh air inlet of the ventilation system to the stale air outlet. Short circuits caused by poor construction techniques can interrupt the air flow needed for proper ventilation, which leads to discomfort, wasted energy, moisture damage, and poor indoor air quality.

3 Thermal Insulation

Most occupied buildings require insulation to achieve some degree of thermal isolation between the external and internal environment. Thermal insulation, correctly installed, forms a complete blanket (thermal boundary) around the heated or cooled area of a building. It is one of the easiest, most reliable methods of minimizing heating and cooling energy requirements. Over the long term, the capital invested in insulation will increase in value, as the value of the energy saved increases with escalating energy costs. Good insulation also makes a building easier to heat or cool, so it is more comfortable to live and work in, and means less fossil fuels demanded in the future.

Determining what type of insulation to use can be rather confusing in light of manufacturer claims and counterclaims regarding their products. Furthermore, factors such as climate, building type, and construction status can also greatly influence the appropriateness of certain materials. The main question is what material to use when and where. Examining laboratory research and field results can help clarify the picture somewhat, but the more that is learned about building thermodynamics, moisture migration, air infiltration, and pressure boundaries, the more questions arise. Answers are not always absolute, and to add further confusion, deciding how to insulate a structure is very context sensitive.

Insulation is manufactured, installed, and sold by its resistance to heat flow (R-value). For a given resistance value, the thickness varies depending on the brand and the material used in making the insulation. Regardless of the thickness and material, the higher the resistance value, the greater the resistance to heat flow and the greater the amount of energy saved. However, some economic boundaries define points of diminishing return.

Desirable Properties of Insulation

In addition to a high resistance value, the following physical properties are desirable and necessary in good insulation:

- stability (nonsettling)

- fireproof or fire resistant
- moisture proof (will not deteriorate or rot when wet)
- vermin proof
- chemically stable and odorless
- clean and easy to handle
- sound absorbing.

Cellulose Fiber Insulation

One type of insulation that has been in use for decades and continues to be used at the present time is cellulose fiber. New approaches to installing this material show great promise for insulating both existing and new structures. Low-income weatherization programs have frequently used cellulose insulation to fill wall cavities and insulate attics. Research conducted along with cellulose insulating activities has furthered knowledge regarding use of the material and building thermodynamics in general. The following sections will provide an overview of important installation issues and summarize significant research findings.

Background

Cellulose insulation is manufactured from recycled newspapers. Various methods are used to shred or desegregate the newspapers into small pieces, which are then treated with boric acid, sodium borate, or ammonium sulfate to deter vermin, retard fire, and inhibit mold formation.

Although cellulose insulation is used primarily in residential-type construction, this does not preclude it from being used in other building types also. Cellulose can be used in both walls and ceilings and can be installed using various techniques. Following is a summary of the different methods used to install cellulose insulation.

Wall Installation Techniques

Blown-in. A common retrofit technique used to insulate walls in existing structures is to blow in cellulose. The common practice is to gain access into wall cavities either at the top or bottom, feed a supply tube in through the hole until the remote end of the cavity is reached, and begin filling with insulation. Installed densities range from 1.3 pounds per cubic foot (pcf) and up. R-values for cellulose range from 3.5 to 3.6/in.

Dense-pack. Dense-pack is a process to blow cellulose into closed wall cavities at relatively high densities that can vary from 3.0 to 5.0 pcf. Cellulose at these densities requires fairly high air pressure to install, which risks damaging walls. Gypsum board, paneling, or other siding materials can break loose from fastenings if not adequately secured to structural members. Two advantages of dense-pack insulation are: (1) a reduction in the settling of the insulation due to its high-density installation and (2) a reduction in air infiltration through building surfaces.

Dry pac. The dry pac wall installation technique is used in new construction and is similar to dense-pack for existing construction. Dry pac uses a fiber-reinforced vapor barrier, which is attached to the interior face of the studs and slit to allow access for the cellulose fill-tube. The cavities are filled to 3 pcf, the slits are sealed, and the wall finishes are installed. The advantage of this system is that it fills voids that frequently do not get filled using pre-cut batts of insulation.

Wet-spray. Wet-spray cellulose insulation is typically installed in situations where the entire wall cavity is exposed from the interior, such as during new construction or during extensive remodeling if the interior wall finishes have been removed. It is sprayed into cavities between studs, screeded flush with the face of the studs, and allowed to dry before being covered. Wet-spray cellulose insulation is installed using water and sometimes an additional binder. Depending on the type of cellulose used, anywhere from 28 percent to slightly over 100 percent of the cellulose's dry weight in water is added to the cellulose as it is sprayed into exposed cavities. Because cellulose fibers are sprayed in place, they fill cracks, seams, and voids. The substrate is covered with a monolithic coating, which helps reduce air infiltration.

Attic Installation

Loose-fill cellulose insulation is either blown or poured into attic spaces. Similar to wall installation, loose-fill densities for the attic are usually in the range of 1.3 to 1.5 pcf. Research results indicate that loose-fill cellulose prevents convective air currents from compromising its thermal resistance (see Chapter 4, **Convection**, p 19).

Technique and Location Selection

Because of the differences between retrofitting an existing structure and constructing a new one, this section is divided into segments for new construction and retrofit application.

New Construction

Cellulose is just one of many options available to insulate a new structure. Cellulose can be wet-sprayed into wall cavities, or filled in behind fiber-reinforced vapor barriers before interior wall surfaces are applied. Either application should effectively seal around penetrations and gaps that would allow air leakage into a wall cavity.

Various factors affect which system to select.

- Availability — certain systems may not be available in some areas.
- Cost — thermally, the various cellulose systems are similar.
- Construction type and schedule — wet-spray cellulose should probably be avoided in fast-track construction situations because of the time required for the cellulose to dry out. Whether to avoid wet spraying somewhat depends on the type of wet-spray application used and the ambient environment.

For attic installation, the insulation is simply poured or blown into the attic space to a depth appropriate to the climate.

Retrofit Applications

Wall cavities in existing structures can also be retrofit using a variety of insulation types such as cellulose, fiberglass, and mineral or rock wool. Most older structures, however, were not constructed to very stringent air-tightness standards and leak considerably through the envelope. Research has shown that cellulose performs somewhat better than fiberglass as an air barrier. In new construction, this is not such an issue because air barriers are typically installed on the exterior of a structure, and the insulation does not need to serve the dual function. However, on old structures without air barriers, the retrofit insulation needs to serve the dual function of insulating and air sealing. Wet-spray is not an option if the wall cavities are not exposed, only blown-in and dense-pack are options. Of these two, dense-pack should be specified for its air-sealing benefits.

4 Technical Issues

Many different technical issues are involved with building thermal insulation. Research has addressed many of these technical aspects, but, in certain instances, has raised more questions than it has answered.

Infiltration

A large part of a building's annual heating and cooling loads can be attributed to infiltration. Air leakage through wall assemblies can be greatly reduced with proper installation of insulation. Using cellulose insulation and the dense-pack technique appears to be promising. Several home weatherization programs have conducted before-and-after blower door tests of houses that were retrofit with dense-pack cellulose insulation (Fitzgerald 1990). Infiltration reductions of anywhere from 36 to 50 percent were measured. Traditional economic analyses of wall insulation retrofits usually account for only the decreased energy flow through the wall and do not account for the additional benefit of reduced infiltration.

Table 1 represents the possible outcomes of strategic dense pack insulating techniques in residential applications. It shows that, in general, for a minimal expenditure a substantial annual savings and subsequent payback can be achieved for existing residential construction. The methodology and techniques used are outlined for each test case (test cases were part of a program sponsored in part by the Wisconsin Public Service Corp.) with installation costs, savings, and payback years also delineated.

Techniques for thermal comfort strategies as listed in Table 1 :

1. Attic strategies used —
 - a. Seal — seal wall tops, etc. with barriers of foam and caulk to reduce convective loops.
 - b. Pack — redo loose insulation to control air movement.

Table 1. The Fox Valley Whole House Project.

Test Case	Conditioned sqft	Attic/ceiling Treatment	Wall Treatment	Floor Treatment	Misc. Treatment	Installation Costs	Annual Savings	Payback Years
94	1601	seal, pack		pack joist		\$ 854.00	\$ 313.00	2.73
49	1398	seal		pack	seal stairwell	\$ 900.00	\$ 212.00	4.24
21	1520	seal,pack	pack	seal transition	seal ducts, poly crawl	\$ 785.00	\$ 181.00	4.35
45	1225	seal, pack,+R20	pack	pack, pack joist	roof vents, seal ret.	\$1,002.00	\$ 220.00	4.56
42	1300	seal, pack,+R20		seal transition	add returns, pack bsemnt	\$1,390.00	\$ 289.00	4.82
20	1224	pack	pack	pack joist		\$1,528.00	\$ 298.00	5.12
41	1344	seal,pack, vent	pack	pack joist	seal returns,	\$1,397.00	\$ 247.00	5.65
92	1392	seal,pack		pack	seal/poly crawl,caulk	\$1,301.00	\$ 203.00	6.42
74	1008	seal	pack	pack	seal/poly crawl,caulk	\$1,600.00	\$ 238.00	6.73
65	1250	seal,pack		pack	+ bath fan	\$1,320.00	\$ 195.00	6.77
24	1230	seal, +R30	seal			\$ 657.00	\$ 85.00	7.71
79	1476	seal,pack	seal,pack	pack, pack joist	seal garage	\$2,854.00	\$ 310.00	9.20
77	1878	seal,+ R20				\$ 245.00	\$ 21.00	11.67
82	816	pack	pack	pack joist	seal/poly crawl, balance	\$1,495.00	\$ 118.00	12.65
5	1144	seal,+R10				\$ 403.00	\$ 28.00	14.29
89	1768	seal,pack	+R19 kneewall	pack	add door to mech. rm	\$ 949.00	\$ 13.00	71.89

Source: Collin and Richardson 1994. Used with permission.

- c. Vent — add attic ventilation.
 - d. +R — add cellulose insulation of specified R value.
2. Wall strategies used —
- a. Seal — seal transition walls between thermal boundary and unheated lower level roof areas.
 - b. Pack — dense-pack walls containing the open end of the floor joist system, second floor only.

- c. +R — add cellulose insulation of specified R value.
3. Floor strategies used —
- a. Seal transition — seal floor at transition spaces between thermal boundary and unheated roof areas.
 - b. Pack — dense-pack entire floor system.
 - c. Pack joist — dense-pack open ends of floor system.

Convection

Heat transfer through homogeneous and fairly dense building insulation is mostly a product of conduction, while at higher temperatures radiation starts becoming significant. Loose-fill insulation exhibits the same trend, with heat transfer by convection traditionally considered negligible. However, experiments conducted at Oak Ridge National Laboratory (ORNL) using an attic test module in the Large Scale Climate Simulator (LSCS) at the Roof Research Center (Huntley 1989), have shown convection to be an important heat transfer mechanism in loose-fill insulation applications when large temperature differences are present (Wilkes 1983). Infrared scanning techniques of the upper surfaces of loose-fill insulations have demonstrated that convective loops can occur when warmer air from the heated space below migrates to the top of the insulating layer. Once at the top, the air cools, increases in density, and descends back into the insulation to create a natural convection loop.

Attic assembly tests conducted from 1990 through 1992 measured the convective energy exchange of various configurations of loose-fill fiberglass and cellulose insulations (Wilkes 1992). Test results indicate that loose-fill fiberglass experienced substantial reductions in its R-value as temperature differentials increased. At the largest temperature differentials tested (72 to 76 °F), the thermal resistance between the bottom of the pressure boundary membrane and the upper layer of insulation was 35 to 50 percent lower than the nominal R values used (R 19-38). Resistances found at smaller temperature differentials (20 to 30 °F) remained close to these nominal values. Covering the assembly with a white polyethylene film and 1-in.-thick fiberglass loose-fill (for stability), actually increased the resistance measurements by 33 to 120 percent, decreasing the heat flow by 24 to 51 percent (larger percentage changes occurred at larger temperature differentials) (Wilkes 1992). The covered condition effectively eliminates the heat transfer by natural convection

(although the configuration is not recommended because of the potential for moisture condensation), and the resulting resistance increases show the importance of the natural convection heat transfer mode.

Similar tests conducted using loose-fill cellulose insulation indicated that the thermal resistance measured actually increased slightly with an increase in temperature differential (Wilkes 1992). If convective occurrences had been significant, the opposite result, which occurred with the loose-fill fiberglass, would have been expected. It could be argued then, that the loose-fill cellulose minimized convective heat loss and decreased energy flows (Conover 1992).

Table 2 (and Figure 4) show annual ceiling heat loads in terms of Btu/sq ft (for a balance point of 55 °F) for 27 cities across the United States (Wilkes 1992). It shows that above 3,000 heating degree days (HDDs), the heating loads indicate a steady and regular increase. As the degrees days increase (increasing the temperature differential), the difference between the cellulose and fiberglass values increase. Interpretation suggests that this increase is caused by convective heat transfer (Wilkes 1992).

Although convective heat loss may increase in loose-fill fiberglass installation conditions, the dollar impact of the convective losses is minimal. In Minnesota, estimates for a typical home with blown fiberglass insulation in the attic indicate expenditures of about \$20/yr in increased energy costs that are due to convective losses (Cushman 1995).

Conductivity

The thermal conductivity of insulation materials varies with form and physical structure, environment, and application conditions. Form and structure vary with the basic material and manufacturing process. Variations include: density, cell size, diameter and arrangement of fibers, degree and extent of bonding, transparency to thermal radiation, and the type of gas present within the insulation (ASHRAE 1993).

Environment and application conditions include: mean temperature, temperature gradient, moisture content, air infiltration, orientation, and direction of heat flow. Thermal performance values are generally obtained from laboratory measurements under dry conditions at specific temperatures and temperature gradient conditions. The design of the envelope, its construction, materials used, and application variations can affect actual thermal performances (ASHRAE 1993).

Table 2. Calculated annual heating loads for fiberglass and cellulose attic insulations.

Location	Heating DD65	Fiberglass (Btu/sq ft/yr)		Cellulose (Btu/sq ft/yr)	
		Loose-fill R19	Batt R19	Blown R19	Settled R19
Miami, FL	189	315	281	274	301
Orlando, FL	543	933	832	812	892
Houston, TX	1363	2100	1864	1821	1997
Phoenix, AZ	1391	2529	2267	2216	2423
Los Angeles, CA	1507	2039	1817	1775	1951
El Toro, CA	1590	2900	2588	2529	2774
Riverside, CA	2083	4150	3672	3591	3919
Waco, TX	2203	3341	2948	2881	3153
Las Vegas, NV	2415	3813	3380	3304	3610
Sacramento, CA	2755	4639	4123	4029	4416
Atlanta, GA	3099	4499	3958	2861	4230
Memphis, TN	3300	4725	4136	4044	4415
Raleigh, NC	3550	5219	4545	4445	4847
Knoxville, TN	3852	5603	4844	4738	5162
Albuquerque, NM	4452	6577	5685	5561	6049
Portland, OR	4602	6703	5944	5808	6366
Washington, DC	4866	7076	6065	5930	6451
St. Louis, MO	4899	7171	6106	5970	6495
Topeka, KS	5247	7976	6605	6454	6995
Seattle, WA	5300	7514	6674	6519	7154
Salt Lake City, UT	5989	8559	7315	7148	7780
Denver, CO	6114	9111	7569	7486	8172
Chicago, IL	6195	8832	7404	7238	7856
Albany, NY	6805	9859	8161	7975	8640
Portland, ME	7353	10746	8915	8708	9447
Minneapolis, MN	8095	12272	9637	9395	10130
Bismark, ND	9022	14172	10938	10644	11463

Note: Heating balance point is 55 °F. Source: Wilkes and Childs 1992. Reprinted with permission.

The effect of thermal conductivity of some insulating materials varies widely with densities applied. Figure 5 shows these variations at one mean temperature. Increasing the densities tested simulates the effect of settling that occurs over time.

Cellulosic fiber insulation remained relatively stable through the densities tested, indicating that settling has little influence on the thermal conductivity of cellulose insulations as compared with some other commonly used fiber materials.

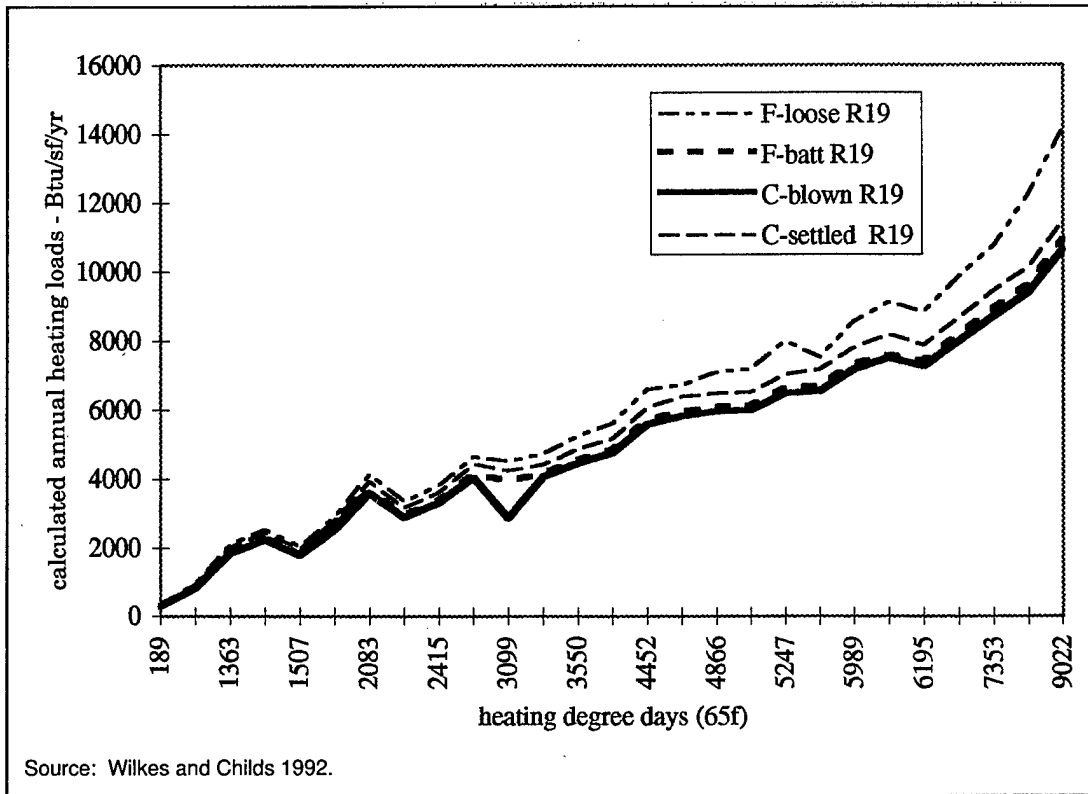


Figure 4. Annual heating loads for fiberglass and cellulose insulation in attic conditions.

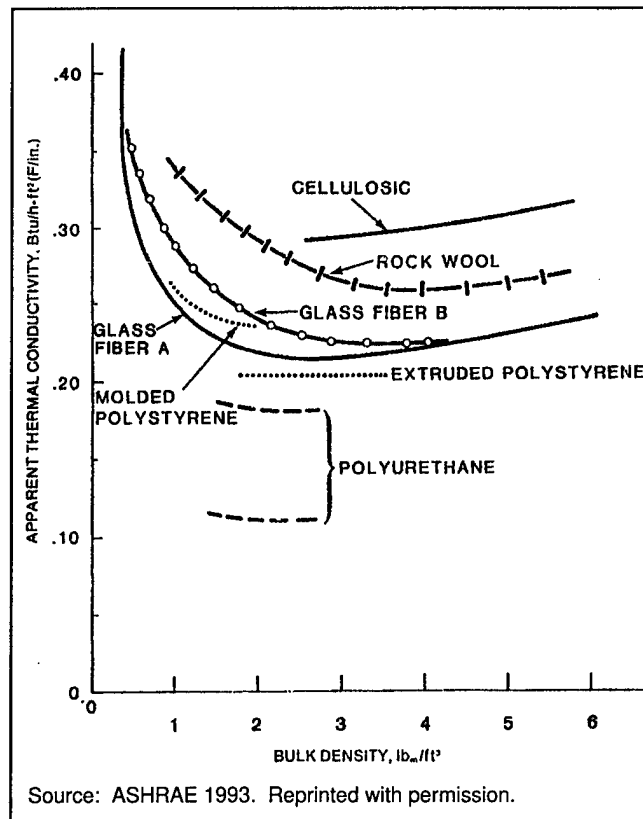


Figure 5. Thermal conductivity vs density.

Thickness Effects

Thermal resistance models for low density insulating materials show that resistance may not always be a function of thickness. Poltz developed a simple model in which the thermal resistance R of a material at thickness L is equal to the resistance of R at zero thickness ($R(0)$) plus the resistance per unit thickness of material (measured at large thickness) times L (Poltz 1962).

$$R(L) = R(0) + R(\infty)L \quad [\text{Eq 1}]$$

The equation can be interpreted as the sum of the thermal resistance of two layers for which there are different heat transfer mechanisms. The existence of thickness dependence in cellulose fiber insulation may be due to radiative effects and moisture gradients (Shirtliffe 1977). (Also see 1993 ASHRAE Fundamentals, first paragraph, p 20.6, which describes the nonlinearity of the radiative heat transfer mode).

Settling

Settlement of cellulose after installation is counteracted either by installing it at sufficiently high densities so it cannot settle, or by using moisture activated acrylic binders or "stabilizers." The settling of cellulose insulation is typically only a concern when installed in vertical cavities at low densities, which is an undesirable practice due to the air-sealing benefits of the dense-pack technique.

Blower Door Testing

Blower door testing places a structure under a known negative pressure condition and establishes how "leaky" the facility is. Weatherization studies have concluded that sealing beyond what is achieved with a well-done insulation retrofit, rapidly approaches diminishing returns. Many programs in the past have emphasized caulking and weather-stripping as weatherization techniques. Current understanding indicates that a significant portion of air leakage is actually through the walls, and once this is mitigated, it is not economically prudent to identify and seal all remaining leaks.

Blower door tests are typically conducted before and after the insulation has been installed. The before-and-after readings can be used to determine how effective the insulation performs in sealing air infiltration paths. Blower door testing usually

depressurizes the interior 50 pascals. This specific negative pressure provides a standard for conducting and comparing blower door tests.

Environmental Boundaries

Two boundaries can be defined as separating the interior environment from the exterior environment: (1) thermal and (2) pressure. The thermal boundary can be thought of as the space or material that impedes heat gain or loss into or out of a building. This material is usually the envelope insulation. A good thermal boundary has a definite temperature differential across it.

The pressure boundary can be defined as the space or material that impedes air movement into and out of the building. This boundary should have a definite pressure differential across it. Which portion of the building envelope serves this purpose is not always clear. Because the pressure boundary exists where the envelope forms the best seal against air leakage and moisture infiltration, a problem arises when the thermal and pressure boundaries are not aligned with one another. Misalignment can allow air leakage paths through the thermal boundary and cause unnecessary heat gain or loss. It can also allow moisture into the insulation resulting in decay or lowered thermal resistance.

The pressure boundary can be identified by using a blower door to depressurize the facility and then measuring the pressure drop across various points in the envelope. If large pressure drops are measured across thermal insulation boundaries, the pressure and thermal boundaries are aligned. If there is a marginal pressure drop across the thermal boundary, then the two boundaries are out of alignment. If out of alignment, air leaks need to be identified and sealed to bring these boundaries into alignment.

Backdrafting

Tightening a building to prevent air leakage can certainly help reduce energy costs, but it can also seriously depressurize a structure creating the conditions for backdrafting to occur. Backdrafting is the travel of air in the reverse direction from what is designed or desired. For example, air flowing down a chimney instead of up, or in an exhaust fan instead of out. This reverse flow of air can become dangerous when exhaust containing carbon monoxide from combustion appliances such as gas furnaces, water heaters, stoves, and ovens is circulated inside of a conditioned space instead of exhausted to the outdoors. Serious health complications up to and

including death of the occupants can occur if the reverse flow of carbon monoxide goes undetected.

To prevent backdrafting, each building should be individually analyzed before tightening to see if the current ventilation system adequately removes the air pollutants or if air leaks are providing this function. Building tightness limits (BTLs) have been established as guidelines for conducting this analysis. BTLs specify the minimum air exchange rate of a building that is necessary to provide enough fresh air to maintain satisfactory health of the occupants and durability of the structure. BTLs are measured in cubic feet per minute (cfm) of air and are concerned only with providing adequate fresh air for occupants with little regard for influencing factors. Therefore, Max Sherman of the Lawrence Berkeley Laboratory created separate tables that take into consideration the number of occupants, the number of stories in a building, and its wind-shielding characteristics. The results of such an analysis after tightening a building can help with tuning the heating, ventilating, and air-conditioning (HVAC) system needed to provide proper ventilation (Tsongas 1993).

Moisture and Vapor Barriers

Most problems that occur in a building's envelope system are moisture related. By contrast, structural problems are rare. Currently, no standards exist for controlling moisture migration in building systems design. While structural design uses standardized engineering principles and formulas, moisture-resistant structural design relies on rules of thumb. In the last few years, several tools have been developed that allow analysis of the thermal and moisture performance of building envelope assemblies. The usefulness of these analytic tools is lessened by the lack of standards or guidelines for design loads (inputs to the models) and for design criteria (interpretations of the output) of moisture and moisture migration. The development of moisture migration design criteria involves quantifying, with a risk management approach, the performance thresholds that distinguish allowable from unallowable design. These criteria should define allowable threshold values regarding mold growth, corrosion, loss of structural strength, and indoor air quality.

Current rule-of-thumb practices for moisture control include: (1) in cold climates, vapor barriers need to be installed on the interior side of the thermal boundary layer, (2) in hot, humid climates, the vapor barrier needs to be installed on the exterior side of the insulation (i.e., the vapor barrier goes toward the "warm side"), and (3) in renovations, paints must be used that retard vapor transmission into the wall cavity. These rules of thumb are currently being studied. New guidelines for

the standardization of moisture control as it relates to geography and building types are being considered for inclusion in ASHRAE standards for design.

Thermography

Thermal imaging tools can be used to investigate and validate insulation installation by quickly identifying cavities that were missed, insufficiently filled, or where insulation has settled. ASTM C 1060 - 90, *Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings*, addresses thermographic inspection of building envelopes. The ASTM standard is a guide to proper use of infrared imaging systems for conducting qualitative thermal inspections of building walls, ceilings, roofs, and floors (framed in wood or metal), that may contain insulation in the spaces between framing members. The procedure allows for the detection of cavities where insulation may be inadequate and where air leakage through the building envelope may exist.

5 Summary

Infiltration control can improve comfort, user satisfaction, and subsequent user productivity. The conscious management of outdoor air infiltration through tight construction techniques and increased thermal insulation values can also reduce energy, maintenance, and equipment replacement expenditures. Moisture migration and indoor air quality are also areas associated with the construction of a building's exterior envelope system and should be addressed with national standards for construction.

For optimum thermal insulation performance, certain physical properties are both desirable and necessary: structural stability, resistance to fire, moisture, and pests, chemical and odor stability, and ease of installation. These properties are the basis for an evaluation of cellulose insulation materials.

Cellulose insulation is made from recycled newspapers that have been chemically treated to have vermin deterrent, fire retardant, and mold inhibiting properties. Installation techniques vary with type of application. Blown-in insulation is a common retrofit technique; dense-pack is the process of installing cellulose into closed wall cavities at high densities; dry pac is used in new construction and is similar to dense-pack installations; and wet spray can only be installed in situations where the entire wall cavity is exposed from the interior.

Dense-pack insulating techniques using cellulose insulation have significantly reduced envelope-related outdoor air infiltration, minimize convective heat loss, and decrease overall energy flows. Age and settling has little influence on the thermal performance of cellulose insulations as compared with some other commonly used fiber materials. Realistic payback estimates for the proper installation of cellulosic insulating materials can range between 2 and 10 yr.

New techniques in weatherization and modeling have improved installation techniques and enhanced the thermal performance of cellulosic insulating materials. These techniques in tightened building construction, along with developing standards for moisture and infiltration control, will enable designers and energy managers to choose thermal comfort strategies more efficiently. These strategies will produce more comfortable buildings with more productive and satisfied users.

Standards and References

Standards

ASTM C 1015 - 84, *Standard Practice for Installation of Cellulosic and Mineral Fiber Loose-Fill Thermal Insulation*. This practice describes procedures for the installation of cellulosic and mineral fiber loose-fill insulation in ceilings, attics, and floors and wall cavities of new or existing housing and other framed buildings.

ASTM C-739 - 91, *Standard Specification for Cellulosic Fiber (Wood-Base) Loose-Fill Thermal Insulation*. This specification covers the composition and physical requirements of chemically treated, recycled cellulosic fiber (wood-base) loose-fill type thermal insulation for use in attics or enclosed spaces in housing, and other frame buildings within the ambient temperature range from -45.6 to 82.20 °C by pneumatic or poured application. While products that comply with this specification may be used in various constructions, they are adaptable primarily, but not exclusively, to wood joist, rafter, and stud construction.

ASTM C 687 - 95, *Standard Practice for Determination of Thermal Resistance of Loose-Fill Building Insulation*. This practice presents a laboratory guide to determine the thermal resistance of loose-fill building insulations at mean temperatures between -20 and 550 °C.

ASTM C 1060 - 90, *Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings*. This practice is a guide to the proper use of infrared imaging systems for conducting qualitative thermal inspections of building walls, ceilings, roofs, and floors (framed in wood or metal) that may contain insulation in the spaces between framing members. This procedure allows the detection of cavities where insulation may be inadequate or missing and allows identification of areas with apparently adequate insulation.

ASTM C 1149 - 90, *Standard Specification for Self-Supporting Spray Applied Cellulosic Thermal/Acoustical Insulation*. The specification covers the physical properties of self-supported spray applied cellulosic fibers intended for use as thermal or acoustical insulation.

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