TITLE: IMPACTS OF RESEARCH EFFORTS ON NEW AND EXISTING BUILDINGS

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IMPARTS OF RESEARCH EFFORTS ON NEW AND EXISTING BUILDINGS

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ABSTRACT

This paper reviews some of the resources for natural heating and cooling of buildings and outlines the potential benefits of specific examples of advanced research. The needs and possibilities for superior glazings, switchable glazings, thermal diodes, thermal transport systems, phase-change material in wallboard, and low-emissivity wall coatings are examined.

BACKGROUND FOR RESEARCH

Energy Consumption. The ultimate reason for research on passive and hybrid solar technologies is revealed in Table I, which shows that roughly one-third of the US national consumption of primary energy is for buildings. Residential space heating alone consumes approximately one-tenth of all energy produced. Thus, improvement in building technologies can influence a significant share of the energy budget. However, the impact of buildings that derive their energy supplies from the environment is not only the energy savings, but is also the societal security that results when buildings remain useful during a severe energy shortage. During the oil embargo of 1973-74, schools and factories were closed and people remained at home to consume the available fuel supply in energy-inefficient houses. In the absence of fuel, a good passive building should remain habitable (if not comfortable) without frozen plumbing, enabling the fuel stocks to be directed to industry and transportation. Passive buildings thereby provide security in addition to energy savings.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>NATIONAL ENERGY BUDGET EXPENDED IN BUILDINGS (Approximate %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residential</td>
</tr>
<tr>
<td>Space heating</td>
<td>10</td>
</tr>
<tr>
<td>Space cooling</td>
<td>1.5</td>
</tr>
<tr>
<td>Lighting</td>
<td>1.2</td>
</tr>
<tr>
<td>Hot water</td>
<td>2.9</td>
</tr>
<tr>
<td>Other</td>
<td>5.2</td>
</tr>
<tr>
<td>Total</td>
<td>27%</td>
</tr>
</tbody>
</table>

Most of the advanced systems and components reviewed in this report have one or more of the following characteristics:

- Independence of building orientation (compass direction);
- Independence of building construction (block, frame, basement, etc.);
- Independence of auxiliary heating/cooling system (forced air, baseboard);
- Serving multiple thermal zones (separate rooms or dwelling units);
- Permitting modular installation and subsequent expansion (add more later);
- Permitting some control of thermal comfort (can be turned off).

Housing Characteristics. Table II shows the numbers of occupied and newly completed housing units in 1983. Approximately 1.5% of the stock is new each year. For future security, it is important that new units be as self-sufficient in energy as possible. However, if appreciable energy security is to be gained during the next 30 years, we must develop passive systems and components that are useful for the retrofit and rehabilitation of the existing buildings. Ideal characteristics of systems for new construction that would also be especially desirable for retrofit, rehabilitation, and multifamily applications are:

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>HOUSING UNITS 1983+ (Thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Family</td>
<td>Multifamily</td>
</tr>
<tr>
<td>Occupied</td>
<td>61,078</td>
</tr>
<tr>
<td>New++</td>
<td>924</td>
</tr>
</tbody>
</table>

++76% of all new units were in the south and west.

*Work performed under the auspices of the US Department of Energy, Office of Solar Heat Technologies.
above characteristics, and thus address the needs of older housing and multifamily housing. These characteristics imply a need for systems that couple collection or rejection of energy at the skin of the building with storage and distribution remotely located in each thermal zone. Multiple zones and remote collection or rejection of energy require the transport of thermal energy, and thermal transport is an important topic for new research.

Heating Resource. The upper limit of the potential solar resource for heating can be illustrated by considering a small rectangular building with 1200 sq ft of floor and projected horizontal roof area, and walls that are 8 ft high. The building dimensions are 50 ft east-west by 24 ft north-south. The building has a heating load of 7200 Btu/DO, which results from R-20 insulation and double glazing. As a hypothetical case, we consider the fraction of heating load that could be met by each day's insolation on the various external faces of the building. Figure 1 shows the fraction of the January heating load met by the insolation at some particularly cold or cloudy locations. (The fractions are increased only slightly if one assumes that excess insolation during one day could be stored for use on a second day.) Note that the insolation on the roof exceeds 80% of the load, and insolation on the south wall exceeds 50% of the load at all of these locations. Because we have considered the coldest month in severe climates, we can confidently predict that in all climates of the continental US, the insolation on the skin of a moderately insulated, skin-dominated building far exceeds the heating requirements. Table III shows the January Solar Savings Fraction of this building for a 300 ft² selective water wall. We conclude that the need for systems that enhance collection efficiency, that enable control, that permit flexibility in building orientation and construction, and that transport energy to or from the thermal storage with low temperature differences. Specific examples will be given below.

Cooling Resource. Two forms of environmental resource for cooling are illustrated in the first two columns of Table IV, which give the average daily minimum temperature and the average depression of the radiant sky temperature below ambient temperature for selected locations where cooling is important. For cooling, the minimum ambient temperature or sky temperature must be less than the desired temperature of thermal storage. Although the radiative resource is actually inadequate in most of these locations, the table supports the general observation that for radiative or ventilative cooling, the resource is available at only a few degrees below the desired temperature, and any cooling process must therefore take place with a small temperature difference.

We conclude that for systems that enhance collection efficiency, that enable control, that permit flexibility in building orientation and construction, and that transport energy to or from the thermal storage with low temperature differences. Specific examples will be given below. 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.

EXAMPLES OF IMPACTS

The operation of a passive heating or cooling system can be conceptually represented by the following diagram.

![Diagram](https://via.placeholder.com/150)

- Heating
- Capture
- Transport
- Store
- Distribute
- Comfort

**TABLE III**

SOLAR SAVINGS FRACTION FOR JANUARY*

<table>
<thead>
<tr>
<th>Location</th>
<th>SSF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seattle, Washington</td>
<td>16</td>
</tr>
<tr>
<td>Buffalo, New York</td>
<td>4</td>
</tr>
<tr>
<td>Great Falls, Montana</td>
<td>23</td>
</tr>
<tr>
<td>Bismarck, North Dakota</td>
<td>20</td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td>43</td>
</tr>
</tbody>
</table>

*300 ft² selective water wall.
The resource must be captured from the environment, and great flexibility is achieved if the energy flow is confined to a volume sufficiently small for transport to storage, from which it is distributed to the demand throughout the building. As indicated in the following impacts of research, advances in efficiency, size, or flexibility of construction may be made in any single process, or by a method that combines all processes.

Capture: Super Glazing. For solar heating, a glazing captures the solar energy. We define the efficiency of the glazing as the ratio of net solar energy transmitted by the glazing to the incident radiation. The efficiency will depend on the temperature difference (heat loss) across the glazing and on the insolation. This is indicated in Fig. 2, which compares various glazings when used as windows with different orientations in various winter climates. The line labeled SG represents single float glass; DG represents double, low iron glass; HM represents double float glass with an internal infrared-reflective layer, and QUAD represents double float glass with two internal layers of high-transmission polyester. These glazings are commercially available. The line labeled 20 AEROGEL represents the expected properties of a 20 mm thickness of Aerogel between layers of low iron glass, and R-18 WALL represents the behavior of a wall with R-18 insulation. The wall provides a net loss of heat under all conditions, as shown by the negative efficiency, but the glazings can provide a net gain of energy. The two upper lines represent hypothetical, but possible evacuated glazings with infrared reflective coatings. The thermal resistance of these hypothetical glazings would be approximately R-12. Existing coatings would reduce the solar transmission of the glazing, with an estimated efficiency as indicated by the lower R-12 line. Ideal optical properties might result in the efficiency

![Figure 2](image)

Fig. 2. Efficiency of various glazings when used as a window as a function of average temperature difference divided by average insolation.
indicated by the upper R-12 line. Either form of this so-called "superglazing" yields a net energy gain for a north-facing orientation in all climates. Such a glazing would greatly increase the efficiency of solar systems in cold climates, and could dramatically alter the heating and lighting of buildings. The properties of a superglazing might be achieved by an actual evacuated glazing, by a 4-fold reduction of the optical scattering of Aerogel, or by a multiple glazing with many high-transmission films. Indeed, in a simulation of a Trombe wall with load/collector ratio of 48 Btu/ft² · °F in Detroit, we find that the annual Solar Savings Fraction increases from 13% with double glazing to 25% with 9 internal films.

Capture: Switchable Glazing. Most of the summer cooling load caused by glazings is due to the transmission of direct, diffuse, and reflected solar radiation. It follows that the summer cooling load could be greatly reduced by an electrically or thermally controlled coating that becomes reflective when activated.4

Capture Through Store: Liquid-Convective Diode. A diode transports heat preferentially in one direction, thus reducing the loss of heat during cloudy or nighttime periods. The liquid-convective diode (invented by T. J. Maloney, patent applied for) should provide about 40% more energy than an equivalent water wall in moderate climates,5 and perhaps much more in cold, cloudy climates.

Capture Through Distribute: Vapor Transport. A vapor transport system (reported in another paper of this conference) should operate with very little loss at night and should maintain the collector temperature close to the temperature of storage, thus enhancing the collection efficiency. Furthermore, this system can passively distribute heat to multiple storage units located throughout the building. This system transports heat downward. It can therefore have the collector located on (or as part of) the roof and thereby be more independent of building architecture and orientation than a passive system that is limited to south wall applications.

Capture Through Distribute: Hybrid Systems. The term hybrid is often used to describe systems that combine active collection with passive storage and distribution, although here we will use the term more generically to refer to systems that transport confined thermal energy to passively discharged storage that is physically separated from the collector, whether the collection and transport are active or passive. Examples of these systems are remote collectors coupled to internal storage walls or masonry floors. A few of these systems have been explored,6,7 but they have not been modeled and tested in depth. The vapor system is another form of hybrid system, as is a collector that delivers heated air directly to the living space with storage in architectural surfaces.8 These systems act as diodes, thus providing greater thermal efficiency than the more conventional passive systems, and the hybrid systems have most of the ideal characteristics listed above.

Storage: PCM Walls. Passive thermal storage has herebefore required massive masonry construction or tanks of water. Containers of phase change material (PCM) have been used, but have not been widely adopted in part because of cost and in part because of their limited area available for heat transfer to and from the containers. In principle, PCM could be embedded in the wallboard and thus distributed throughout the building. For a direct gain building with interzone convection (forced or natural), wallboard with 21 Btu/ft² latent heat yields the same predicted energy savings as the recommended amount of masonry.9 Such distributed thermal storage could thereby enable passive and hybrid systems without departure from conventional frame construction practice.

One might expect PCM walls to be useful for cooling. Because (in principle) the energy is stored and released at a single temperature, rather than over a range of temperatures as occurs with sensible storage, the cooling resource can have a higher temperature if PCM storage is used. To explore this possibility, we note that the heat transfer rate at the surface of wallboard (U-value) is approximately 1 Btu/ft² h·°F. For example, if the air passing over the surface of the wallboard for 1 hour is 5° cooler than the wallboard, or if the air passes for 5 hours with 1° of temperature difference, 5 Btu will be removed from a square foot of storage. If the cooling capacity of wallboard were to be charged at night by ventilative cooling, a measure of the cooling resource is therefore the total number of degree-hours that the ambient temperature is below the phase-change temperature, 1. If we assume that all of the stored cooling is used during the day, the daily upper limit of cooling is the total latent heat of the wallboard. That is, if the wallboard has 21 Btu/ft² latent heat, a maximum of 21 degree-hours of ventilative cooling can be used. The last four columns of Table IV show the average daily cooling potential for wallboard with a transition temperature of 68°F and 21 or 30 Btu/ft² latent heat, and with a transition temperature of 75°F and the same latent heats, respectively. Table IV illustrates a worst-case condition; the cooling potential would be greater in months other than July. We notice that the available July resource is strongly dependent upon the transition temperature.

To give significance to the K numbers of Table IV, we note that the 1200-ft² house of the previous example might contain 3600 ft² of wallboard. A cooling potential of 20 Btu/ft² (72,000 Btu/day total) would occur with K of 20 degree-hours, and this condition is met or exceeded on the average July night in several entries of Table IV. (Seventy-twé thousand Btu of cooling equals 6 tons of refrigeration, which is roughly the output of a window box air conditioner operating at full duty for 12 hours.) Because the hypothetical wallboard has some cooling benefits in these severe climates during July, we may conclude that PCM wallboard should be useful for cooling in many climates, and that a detailed, full-season system study is justified.
TABLE IV

VARIOUS ESTIMATES OF COOLING RESOURCE IN JULY

<table>
<thead>
<tr>
<th>Location</th>
<th>$T_{\text{min}}$</th>
<th>$\Delta T_{\text{sky}}$</th>
<th>$K_{21}(68)$</th>
<th>$K_{30}(68)$</th>
<th>$K_{21}(75)$</th>
<th>$K_{30}(75)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago, IL</td>
<td>66</td>
<td>13</td>
<td>7</td>
<td>9</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>Washington, D.C.</td>
<td>65</td>
<td>14</td>
<td>7</td>
<td>8</td>
<td>20</td>
<td>27</td>
</tr>
<tr>
<td>New York, NY</td>
<td>66</td>
<td>16</td>
<td>7</td>
<td>8</td>
<td>20</td>
<td>29</td>
</tr>
<tr>
<td>St. Louis, MO</td>
<td>69</td>
<td>16</td>
<td>2</td>
<td>2</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>82</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Brownsville, TX</td>
<td>75</td>
<td>13</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>71</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

$T_{\text{min}}$ = average daily minimum temperature.

$\Delta T_{\text{sky}}$ = average daily sky temperature depression, adopted from contour map in Ref. 2.

$K_{21}(y)$ = average daily degree-hours below temperature $y$ with a daily upper limit of $x$.

**Comfort:** Radiative Heating and Cooling. The temperatures of the air and of the infrared radiation within a room are not necessarily the same. The human body responds to an equivalent temperature that is approximately the average of these two temperatures. If some of the walls have low emissivity (high reflectance) in the infrared, the body will feel the radiation from the other surfaces because it is reflected from the low-emissivity walls. If the space heating were provided by a radiative source such as a Trombe wall or other heated surface, the air temperature could be decreased while the radiation provided the desired thermal comfort. Likewise, if cooling were provided by a large cool wall, the other reflective surfaces would permit the air temperature to be higher than the usual thermostat set-point. Reflective inner surfaces on exterior walls might be of extra benefit in older, poorly insulated buildings where discomfort is presently caused by radiation from the exterior walls. Wallpaper or paint with reflective properties in the infrared would appear quite ordinary to the eye and thus be acceptable to the consumer.

**CONCLUSIONS**

- An adequate solar resource for heating exists. The resource of the roof is especially large.
- Advanced glazings can capture this resource, even on non-south surfaces.
- Switchable, reflective coatings can reduce the cooling impacts of glazings while retaining the heating benefits.
- Thermal diodes may double the efficiency of passive systems in cold climates.
- Systems for retrofit, rehabilitation, and multifamily applications will need heat transport between the roof or south facade and the interior of the building.
- Vapor systems can provide the desired transport and provide increased efficiency because they move energy over long distances, at low temperature differences, with diode action.
- PCM-loaded wallboard can serve as thermal storage for heating and cooling.
- Low-emissivity paint or wallpaper should add thermal comfort and reduce energy consumption.

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**REFERENCES**

