

The Active Thermal Manifold Skin: Feasibility, Prototyping, and Performance Studies of a Wall System Integrating Distributed Solid State, Solar Powered Cooling and Heating Technology

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Abstract

The following project proposes the study of a solid state, solar-powered distributed cooling and heating system for integration in building skins, and the architectural implications of such a system. As opposed to centralized HVAC systems, the project's subject of examination is a decentralized system of cooling using an array of inexpensive, independently responsive units with collective intelligence.

The basis of the proposed cooling system is the application of photovoltaic panels to power thermoelectric cooling modules. Supplied with an electric current, thermoelectric devices transfer heat from one side of the device to another, heating one side while chilling the other. In summary, the proposed system would work as a compact, microprocessor-controlled unit consisting of a thermoelectric module, a photovoltaic panel, exterior heat dissipation plates, and an interior cooling plate with condensate discharge and fan. The innovation of the proposed concept, distinguishing it from past proposals for thermoelectric building cooling, is its potential integration in the building skin as a distributed array of independently functioning units.

Through the construction of a series of prototypes, the feasibility, performance, and architectural implication of these 'micro-cooling' systems will be studied. Constructed at full scale and instrumented with monitoring devices, a final functioning prototype will simulate the performance of the proposed system under realistic conditions, while monitoring an identical, unconditioned prototype in parallel. These proposed prototypes intend to both demonstrate the raw technology of the proposal and, using advanced modeling and fabrication methods, explore the design, assembly, and integration of the system's components in the building envelope.

1 Introduction

The following research proposed, as its premise, to explore the potential of integrating solid-state, photovoltaic powered thermoelectric devices into an architectural wall system. It is recognized in the thermoelectric industry that an architectural-scale application of thermoelectric technology presented imposing issues. Thermoelectric modules, small chip-like devices which employ direct current to operate as solid-state heat pumps, are effective for cooling and heating in a variety of applications, but at an architectural scale their relative inefficiency compared to conventional methods of heating and cooling presents a challenge in understanding how they can be useful in buildings. Unlike conventional cooling and heating systems, however, the physical characteristics of thermoelectric devices allow them to be directly integrated to building skin assemblies.

1.1 Hypothesis

Thus the research was hypothesized to produce, as its final result, a prototypical system synthesizing the science of thermoelectric devices, possible design strategies based directly on their performance, and emerging materials and fabrication methods. The differing point between this research and existing research activities in architectural thermoelectric applications is based in the notion of a distributed thermoelectric system. The completed prototype (to be discussed in detail later in this report) is based on this concept: applying the thermoelectric devices not in concentration in a particular area, but in a way which arrays the cooling and heating points across a larger area. Part of this approach is the promise that the devices can work from within, rather than scattered around the architectural systems. Thus the research has touched on several points at once, ranging from thermoelectric technology integration, building physics simulation, material strategies, photovoltaic design methods, and so on. This report presents the initial phases of research, and will provide a technological and architectural context for the research.



Figure 1: Two full scale prototypes constructed as part of the research; the prototype in front is complete except for photovoltaic systems, which had not shipped at the time this report was submitted.

1.2 Overview of Thermoelectric Technology

Thermoelectric technology is based on the long-known Peltier Effect, when a junction between two conductors of a particular material cools or heats in response to an electrical current. Since this phenomenon's documentation in the mid-19th century, 'Peltier junctions' have greatly increased in efficiency and been reduced in their size and production complexity, yielding today's modern thermoelectric industry.

The modern thermoelectric or TE module is a flat wafer composed of an array of miniaturized bismuth telluride alloy junctions, connected electrically in series but operating thermally in parallel. Under operation, the module works as a heat pump, with a particular amount of heat transferring from one side of every junction to the other side of the device. In total, this yields a hot and cold side for every module. Modules are powered by relatively high current but low voltage DC currents. TE modules, as a result of the properties of thermoelectric junctions, may be run in either direction, pumping heat or cooling either side of the device. Start-up of the thermoelectric process is nearly instantaneous and they may be easily controlled to maintain particular temperatures. Modules can also generate electricity as a result of temperature differentials, and this property has been a dominant subject in recent research.

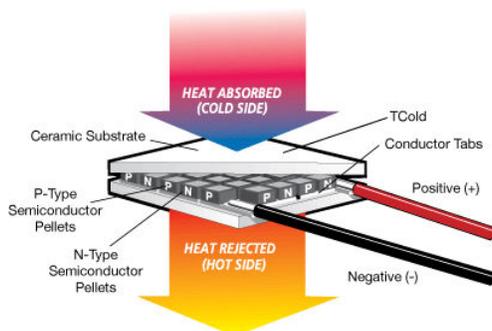


Figure 2: Thermoelectric module diagram showing 'heat pumping' and system of internal Peltier junctions. (Image courtesy of Tellurex, Inc. and used with permission)

The many advantageous properties of TE devices has led to a wide range of applications, commonly in specialized cooling applications. Today this technology can be found in DC-powered cooling devices such as coffee cream chillers and small beverage coolers. More interesting applications have been found in the auto industry, where Honda, among other manufactures, has featured cooling systems integrated into automotive seats. NASA is perhaps the most well-known early developer of TE technology, using TE modules for cooling space suits and for generation in small nuclear-powered battery systems.

Coincidentally, the direct current power supply required by typical TE devices is entirely compatible with photovoltaic (solar) generated power, a property on which numerous devices and inventions relating to refrigeration and cooling have been based.

While TE coolers of over 300W capacity have been manufactured [1], the technology is still considered to be appropriate for only specific ‘tasks’ rather than cooling or heating at the scale of the architectural environment. Perhaps the most significant contributor to the lack of enthusiasm for TE applications in buildings is the relatively inefficiency of the devices: the module used in this research is rated with a Q (heat transfer, air to air) of 22 W, while requiring 72 W of power to operate (12VDC*6A). This results in a coefficient of performance (COP) of 31% - far less than conventional air conditioning or heat pump systems that usually have COP’s in excess of 300%. Rather than substitute one technology for the other, recent research has proposed ‘hybrid systems’ using TE’s and conventional compressor-based cooling systems in conjunction.[2]

Yet the field of TE research has been consistently materials-driven and discoveries and improvements in the production of the TE junctions may improve efficiency substantially in the future. There is no indication from within the field of TE research that groundbreaking efficiency improvements are unlikely [3] and even recently researchers have discovered a new process for creating junction alloys using nanomaterials. [4]

Current research in the integration of TE technology in architecture has resulted in at least one rigorous study that produced a functional prototype, emerging from the work of Prof. Steven Van Dessel and a team of researchers at Rensselaer Polytechnic Institute [5]. The system developed is referred to by Dessel as an Active Building Envelope (ABE) and is based on the integration of thermoelectric devices at or around the window opening. The most recently published prototype (Feb. 2008) employs eight thermoelectric modules powered by 45 W of converted DC power (a PV system is under development but is not represented in publication), driving heat transfer via water-filled aluminum tubes installed adjacent to a window opening. Tested for cooling and heating, this system successfully achieved thermal impacts on a one cubic meter insulated volume. [6]

The same group of researchers has recently moved from the scale of conventional TE modules to the development of highly miniaturized TE’s and photovoltaic cells that can be used to laminate glazing or wall surfaces. [7]

1.3 Concept Description and Relevance

The general integration strategy in the ABE research is to apply the thermal work of the TE modules to a conductive material directly – the aluminum tubes in the recently published prototype, and glazing in the more futuristic lamination strategy. This presents a significant difference between the ABE research and the research described in this report.

Rather than apply the thermal work directly to a conductive part of the wall construction, a strategy was sought in which the modules can apply thermal work to the air mass of room. Such a strategy suggests immediately that the TE modules should be distributed, or spaced, so that heat transfer is also distributed. The performance properties of TE devices supports this strategy of dispersion, since the coefficient of performance of TE device is independent of cooling load – thus making it equally effective to use a number of smaller modules over a single, centralized module. [8]

In effect, the integration strategy pursued sought a method to integrate TE devices with an air volume, rather than with a conductive surface – it would be this air volume that would function as a sort of heat exchange vehicle. The TE devices employed in the research are specially designed air coolers, designed to exchange heat with ambient air on the cold side (as opposed to a cold plate), using fan-supported heat sinks on both hot and cold sides of the device. Originally this approach was perceived to present an insurmountable bottleneck with efficiency. However, due to the heat pump nature of the TE module, it is the hot side of the device (where heat (Q) is being transferred and exchanged with the environment through the hot side heat sink) that determines the efficiency of the system. Performance on the cold side of the device is related directly to the cooling load. Increasing the cooling performance is about managing this load in design, either by manipulating the air volume around an individual TE or by adjusting the spacing and distribution of volume among devices. Thus the relationship between air exchange and the TE device is the basis for the concept of a distributed system: a very different system from conventional HVAC systems that resulted in a very different integration approach.

The sizing and appropriateness of a distributed TE heating and cooling system has much flexibility that cannot be realized with conventional HVAC methods. It is typical to cite the many advantages of TE’s over mechanical systems: they have no moving parts, make no noise, can function maintenance free for long periods, and can be controlled electronically with few limitations. However, the most critical point to be made in TE’s integration with architecture is their ready integration with photovoltaic power sources. TE devices operate acceptably with variable power supplies (even with lower voltage or current than that for which the device is rated – a reality of exclusive use

of PV power) and can be switched on and off (by computerized controls or other means) without the need to develop any momentum within the system as in compressor-based systems.

On the other hand, conventional HVAC and PV technology are less compatible. A small central air conditioning system rated at 18000 BTU/hr output will average 1385W of power consumption over seasonal operation to power both compressor and fan [9]. This is a high coefficient of performance (COP) at about 3.8 or 380% efficiency and we may conclude that it is feasible to power this air conditioner with a PV array of 1.5kW. However, the power consumption curve for this air conditioner is variable: systems of this size can draw as much as 14-15 amps during operation of both compressor and fan – approximately 3.1 – 3.3 kW given 220V power. When the compressor idles or the fan shuts down, consumption decreases dramatically. Photovoltaic systems in which batteries and power supply implements must be carefully and economically selected are simply not fit for conventional air conditioning, although a newly available solar assisted air conditioning system from Lennox employs a PV array to run the fan during peak cooling loads [10].

The apparent radical difference in efficiency of a TE-based distributed cooling system and a centralized HVAC system – 31% vs. 380% respectively – begins to erode, however, given the actual efficiency of the systems and their power sources. The central air conditioning is tied to the electrical grid, which after efficiency losses attributed to the production and transmission infrastructure is currently a mere 32% when it reaches the typical American household, as measured by the most recent data from the Department of Energy [11]. The second deficiency of the centralized system is its method of conditioning – by forced air – which can be highly problematic. The US Dept of Energy reports that typical pressurized duct-based, centralized HVAC systems lose 25 to 40% of their heating and cooling output through the ducts, either through imperfections in supply/return pressure and ductwork [12]. Based on these observations, generating electricity off-site for a centralized HVAC system may be between 30 to 50% efficient compared to the 26% rated efficiency for the TE-based system (including an 85% derating factor for the battery-based PV system) used in the current research. While comparing the two technologies is complex – and is beyond the scope of the research – it is clear that using TE's with solar power can be a viable source of green heating and cooling, considering the advantages of using on-site energy. The research hopes to demonstrate further that the use of TE technology carries with it new possibilities for building climate control and integration of systems into building skins far beyond what conventional HVAC systems can introduce.

1.4 Development Towards a Distributed, Double Skin System

Determining the direction in which the TE's, photovoltaic, and wall components could be integrated was an important step in the early stages of research. This process began with the realization that moderately-sized TE air coolers were matched closely to commercially available photovoltaic panels: a cooler with 72W power requirement could be powered realistically with an 85W photovoltaic panel. This one-to-one relationship informed the direction in which the building integration problem was oriented. For example, it is unrealistic given this one-to-one relationship between PV panels and TE modules to cool a load of one ton (12000 Btu/hr), which is common for small buildings and offices: too many TE modules would quickly require more PV's, which would overpopulate the wall and roof areas.

While the research had already identified the building skin as the area where TE integration would be explored, the wall became the target cooling and heating area as well. Walls are subject to two primary sources of heat transmission: conduction through the envelope and incident solar radiation (insolation). These sources of heat transmission become highly critical in the design of conventional HVAC systems, given that the large drop in thermal resistance at doors and windows necessitates the location of radiators and HVAC ducts in close, if not direct, proximity. Commercial curtain wall systems often have their own fan-coil units for heating and cooling the immediate area around the glass.

TE's could, hypothetically, operate not only with proximity to these areas of reduced thermal resistance, but within these assemblies. If the TE modules were distributed within or mounted on these assemblies, they could reverse the impact of heat loss or gain on the interior environment. Yet thermoelectric devices, combined with glazing, could be built into the window framing or mullions, or distributed across its surface. These applications, however, are less effective in isolating the TE's cooling and heating impact on skin loads. A different approach was needed that could control the relationship of the surrounding air volume, temperature, and pressure to the TE device. The approach which was adopted considered the air surrounding the TE installation to be a secondary heat sink. A defined heat exchange geometry dependent on resistance and differentials in pressure, temperature, and density, this volume of air could function as an active thermal manifold through the heating and cooling of the TE module.

2. Development of the Active Manifold Concept

2.1 Double Skin Systems and Relationship to the Active Manifold

The notion of a thermal manifold is not new in building skin design and engineering: it is closely related to the double-skin (or double-leaf) façade systems. These systems have their origins in the research and work of Mike Davies, who developed the ‘polyvalent wall’ concept for Pilkington, which intentionally combined the daylighting benefits of glazing with the passive solar potential and ventilating potential of an engineered and technically developed cavity wall system. [13]

The dominating concept behind these systems is the ability to use massive amounts of glazing in a building without the penalty of heat loss and gain typical through glass. Double skin wall systems, however, have been adopted to serve varying functions – in some buildings, they take advantage of the stack effect for hot exhaust air ventilation, while in others they are unventilated and serve primarily for passive solar heating by collecting solar gain. [14] Decades of observation have demonstrated that double skin envelopes can be problematic, however: engineers have noted that double skins designed primarily as a thermal buffer primarily for winter must have a secondary ventilation strategy for summer to prevent overheating. [15] Secondly, double skin systems facing south will generally neutralize their energy impact over double glazing by actually preventing beneficial direct solar gain. [16]

While early double skin facades were premised on simplicity and passive ventilation, it is now evident that the seasonal and daily climate fluctuations make it imperative that the systems be fully controlled and automated – since poorly functioning double skins have been found to actually increase energy consumption. [17]

Controls for double skin facades typically amount to automated vents, baffles, windows, and shading devices – generally serving to enhance the influence of passive strategies using solar gain. Many of these strategies use differentials in temperature (effectively equating to differentials in pressure or density) to control exchanges of air and heat, although the only vehicle for moving air is solar gain.

Adding TE technology to this system introduces a new, formerly impossible ability to control these fluctuations by taking advantage of the cooling and heating capability of TE modules. Because of elementary thermodynamics, systems of relative stability are predictable: TE units within a double skin system can be intelligently controlled to respond to climate conditions both in the double skin envelop but also within the interior of the building in certain conditions. These TE units could also provide heat within the thermal buffer, helping to offset the loss of direct solar gains on cloudy days or as a result of the wall construction.

The result of the combined technology of the double skin and solar powered thermoelectric arrays is an active manifold system – a wall system that can hypothetically control both internal heat and air exchange as well as exchange heat under some conditions with the interior. Like the original polyvalent wall, this system is intended to be extensive in an architectural context: not just an opening, but an entire wall surface. The extent of the system and the dispersion of the TE modules would make this a distributed system, where the modules can relate to individual portions of the double skin cavity. Moreover, as a transparent or semitransparent skin, this active manifold would serve as a daylighting system. Unlike traditional HVAC systems that in order to maintain efficiency need fully sealed envelopes with minimal penetration, this system could be used as frequently as necessary: the active function of the manifold and the daylight could together save large amounts of energy. This is the complete integration of environmental imperatives: the energy saved as a result of daylighting alone may reduce the total electricity consumption in housing by 6.6% and in commercial buildings by 28.5% based on recent statistics, [18] further improving the value of the active thermal manifold system as a polyvalent skin.

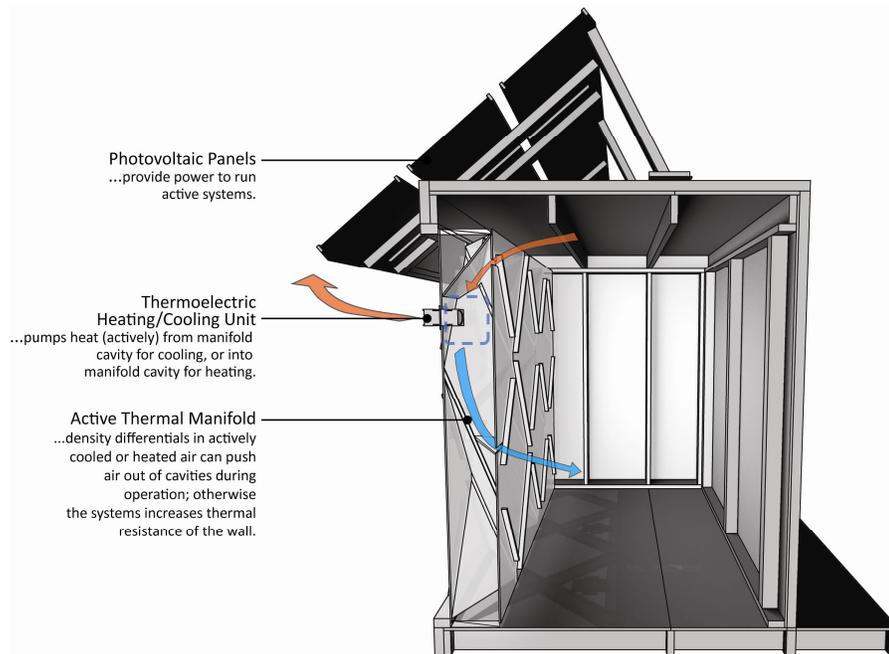


Figure 3: Schematic view of prototype showing PV system, location of thermoelectric units, and the active thermal manifold.

2.2 Prototype Initial Design and Development

The initial concept for the thermal manifold was based on a conventional glass double-skin system with a single horizontal row of thermoelectric devices. The devices were assumed to be air coolers, with aluminum heat sinks on each side that included a fan for drawing air through the sink. The hot side heat sink would be completely outboard of the outer glazing, while the inner, cold side heat sink would be contained within the double skin cavity. Mounted directly above the devices at an optimal average inclination was conceived a row of photovoltaic panels, roughly one panel for each TE device. The location of the photovoltaic panels above the TE modules would shade the heat sinks from direct solar gain: too much additional heat on the exterior of the module could cause efficiency loss and even conduction to the cold side through the module interior.

Very early in the process of design it was identified that façade-mounted PV arrays of the scale involved in the project were prohibitive—increasing the inclination of the PV to prevent overshadowing on a multistory wall resulted in substantial drops in predicted outputs (reaching nearly 50% of output in an optimal installation). Thus it was elected to move the PV's to the 'roof' of the prototype and decouple their direct architectural integration from the research objectives, consequently choosing the relationship of the TE units to the double skin cavity as the primary area of investigation for the research in terms of architectural integration.

The initial assumption for the operation of this design was that the TE module would cool the cavity and, as the air in the cavity cooled, it would become denser and 'drop' from the cavity. If the cavity opened to the interior, this dense air could leave the cavity. A stable displacement of air in this manner would create negative pressure at the top of the cavity, where warm, less dense air would accumulate. A second set of openings at the top of the cavity would draw replacement air from the room beyond in response to this negative pressure. This cycle within the 'thermal manifold' would be perpetuated under two conditions related to the second law of thermodynamics: the temperature differential would be maintained between the top and bottom of the cavity by way of the TE module, and that the coolest temperature within the manifold would be reasonably cooler than the interior temperature so as to permit the dropping out of cavity air. Hypothetically, a similar temperature differential during active heating would cause air to move out of the active cells through the top, and draw in air from the bottom. In extreme hot or cold scenarios, the manifolds may become warmer or cooler than the interior volume, in which case air flows would reverse in order to reach equilibrium with the air: under these conditions, the manifold and TE's would be functioning as a thermal buffer working against conduction. These assumptions have been confirmed by preliminary experiments and continue to inform the expectations of the current research phase.

In late August 2008 a ‘desktop’ scaled model was constructed using an A22 TE air cooler built by Tellurex of Grand Rapids, Michigan. This cooler model was an air cooler, and thus had dense vertical fin aluminum heat sinks factory applied to each side. Each heat sink had its own 0.45A fan, which was important on the cold side for increasing the rate of cooling and increasing the volume of air available for heat exchange on the cold side. The fan also decreased the possibility of condensation on the cold side heat sink by keeping air moving around the fins, which can easily develop with delta T of 20 degrees or more. The particular TE model was perceived as a likely candidate for the final prototypes, so it was determined to be the most useful unit to buy.



Figure 4: Desktop model with single A22 TE air cooler from Tellurex, inc installed in an double skin cavity of approx. 14”W x 14”H x 8”D. Insulation had not been applied to the enclosure when this image was taken.

The desktop model itself was a small container constructed of 3/4” plywood and insulated on bottom, top, and side using 1” polystyrene rigid insulation. Each end of the container was framed with 1/4” plexiglass, and an extra dividing wall of 1/4” plexiglass was added 8” back from the front glass surface. The 8” space represented a small double-skin system. Cutouts were added to the top and bottom of the dividing panel to allow for air exchange between the main volume and the double-skin cavity.

Before the desktop model was tested, a series of brief calculations were completed to assess the feasibility of a group of A22 TE air coolers in offsetting cooling loads associated with an envelope:

The hypothetical envelop was 12’ long by 8’ high.

Heat gain by conduction was calculated using the formula:

$$Q = A \times U \times \Delta T$$

Where the exterior surface area of the envelop:

$$A = 8.92 \text{ m}^2$$

The thermal resistance of typ. alum double-glazed curtain wall (low-E coating on #3 surface)

$$U = 2.0 \frac{\text{W}}{\text{m}^2 \cdot \text{°K}}$$

And the assumed temperature differential from the exterior to the cavity was approximately 7°K or 10°F (realistic for a scenario in which the exterior air may be 85 and the cavity wants to be maintained at 75)

Heat gain from conduction:
$$Q = 8.92 \text{ m}^2 \times 2.0 \frac{\text{W}}{\text{m}^2 \cdot \text{°K}} \times 7 \text{°K} = 125 \text{ W}$$

Heat gain from insolation (incident solar radiation) was calculated for the latitude of Muncie, IN using the summer peak average of 2.16 Wh/m² multiplied by the exterior surface area of the envelop $A = 8.92 \text{ m}^2$

Heat gain from insolation:
$$Q = 19.3 \text{ W}$$

Total heat gain for the hypothetical envelop:
$$Q = 144 \text{ W}$$

The total heat gain through the envelop in a conventional glazing system would end up as heat in the interior air volume. In a double skin system, this heat would be accumulated in the interior cavity. So while this total heat gain is a serious challenge when compared with the relatively small capacity of the thermoelectric cooler, the relationship between envelop heat gain and the cavity volume can be part of a strategy for developing a better cooling load condition for the TE devices. In other words, providing a more reasonable chunk of cooling load will allow a TE devices to work within their heat pumping capacity.

The strategy which emerged from this problem with cooling load and the double skin was not to add more TE modules...rather, it became apparent that the double skin volume itself could be partitioned in a way which reduced the exposure of the TE's cooling load to the external skin while maximizing exposure of this load to the interior. The simplest manifestation of this strategy is introducing a folded partition that defines alternating inward-outward volumes with an extruded triangular shape. In this configuration, half of the cavity faces exclusively to the exterior, while the other half faces exclusively to the interior.

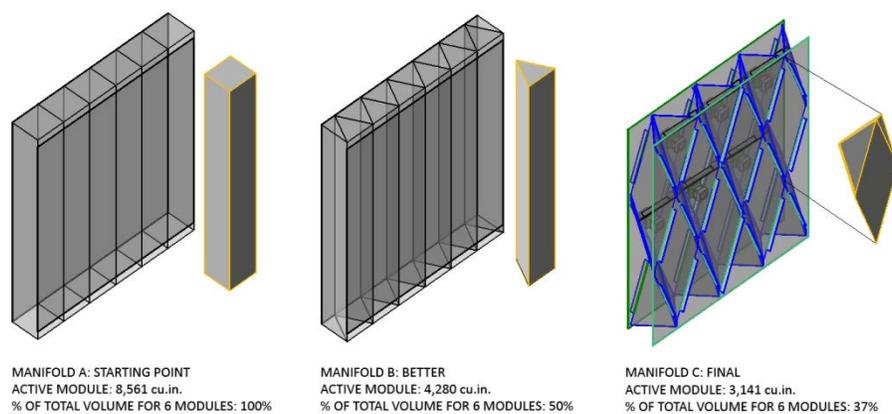


Figure 5: Comparison of different methods for partitioning double-skin internal cavities to produce more effective geometries for cooling/heating load.

In terms of heat transfer, there are two ways to see this strategy. The first is that in introducing further internal material layers, the conductive heat gains are reduced, since heat must travel through at least two layers to reach an inner cavity. The second is related to cooling work, which removes a particular amount of heat energy per unit volume: less volume, even at the same temperature, requires much less work in removing heat. Adjusting the shape of volumes within the double skin could effectively reduce the effect of external gains on the TE unit and allow the unit to function more in the capacity of a buffer to interior spaces. Separated from the higher external gains, the TE unit can reach lower cold side temperatures as well, increasing the potential to create useful temperature differentials. The complexity in calculating exactly how this works is daunting; likewise, a computer-based simulation that combines the effects of convection, conduction, material properties, geometry, and the concentrated cooling effect of the TE devices was not feasible in the current academic semester.

Instead, a brief experiment was carried out, using the desktop prototype, which examined the effect of introducing a partition to the double skin cavity. At the time, a photovoltaic power system was not implemented for the prototype, and instead a AC to DC convertor was used to power the TE module. The test was carried out on October 10, 2008 during an unseasonably warm afternoon. Ambient temperature, measured in the shade with a Kester handheld weather instrument, was between 79.8 -82.0°F . Temperature readings for each heat sink (measured with thermocouple probes secured in contact with the sinks) and a set of temperature readings from inside of the prototype (collected with synchronized Stow-Away temperature loggers) are noted in the tables. A small shading projection was added to ensure that direct sunlight was not falling on the sensors, but left approximately 75% of the double wall cavity exposed.

A partition was constructed of extruded polyethylene plastic 5mm in thickness (with an approximate U value of 0.43) which divided the double-skin cavity roughly in half; however, the surrounding seams around this partition

could not be sealed due to the construction of the prototype. The model was positioned facing west, to introduce direct solar gain: with a clear sky and consistent sun, insolation levels were quite high. The perforations in the dividing panel were taped up so that only approximately 2 sq. inches remained for air to exchange at the top and bottom of the cavity wall. The test involved first running the TE in the cavity without the partition, then opening the model and flushing it with fresh air, and then adding the partition for a second run of the TE device in the partitioned cavity. Four synchronized Stow-Away XTI temperature loggers were used to collect temperature data.

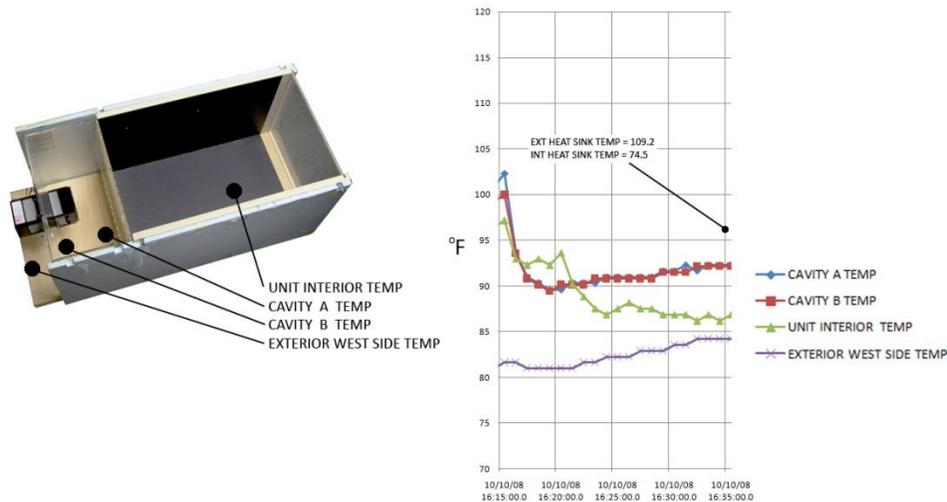


Figure 6: Cooling test without partition in place in the cavity. Note two cavity sensor readouts remain equal and some cooling is achieved on interior while exterior temperature was rising; also, increasing temperature in the cavity is equal to exterior temperature increases, showing the TE unit had reach a stable delta T.

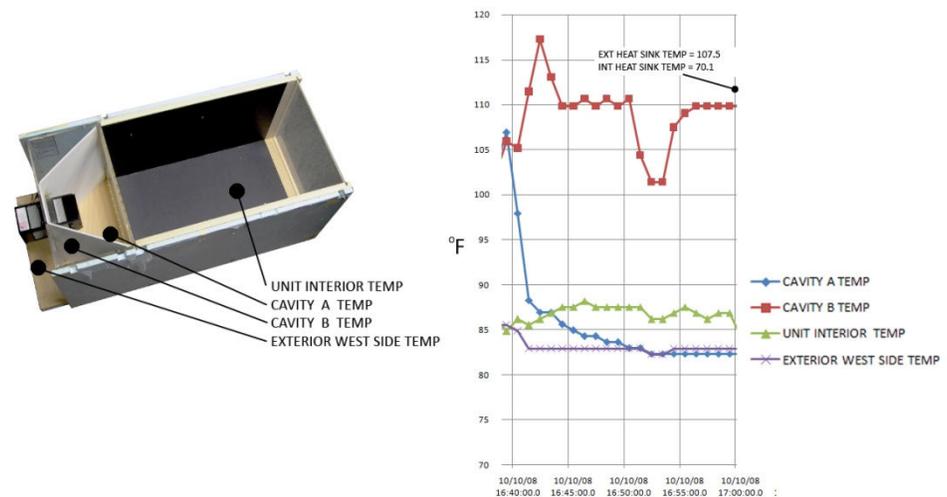


Figure 7: Cooling test (following that shown in figure 6) where a partition is introduced. Note substantial difference in cavity temperatures is realized immediately; internal cavity becomes cooler suggesting that some convective exchange occurring between cavity and interior.

Weather conditions prevented further experimentation with cooling under real conditions, although the brief experiment demonstrated the effectiveness of the partition in buffering the TE device from high temperatures. The consequence of the partition is that the cavity temperature, which had formerly risen to levels above the main interior volume (perhaps as a result of a huge amount of direct gain), were quickly dropped to a temperature that was actually lower than the main interior volume. The latter condition would hypothetically result in air exchange due to density differentials – an active thermal manifold.

The expected effect of the active thermal manifold – a cyclical exchange of air driven by temperature-pressure-density differentials – was examined in second experiment using the desktop prototype, this time indoors. The testing method observed observation of air flows using titanium tetrachloride, a compound that, when released into the ambient air, reacts with moisture to yield a chemical smoke. Again, the perforations in the inside panel of the double skin were partially covered. The prototype was outfitted with a 40W incandescent light bulb, suspended in the rear of the unit, to establish a cooling load. Additionally, a switch was added to the interior-side heat sink fan of the TE unit – switching this fan off during the release of the titanium tetrachloride ensured that turbulence created by the fan would not affect air circulation, and that any observed circulation would be the result of convective currents alone. With the TE running, smoke was drawn based on temperature differentials alone from the interior space into the cavity and out again. The experiment demonstrated that a cooling source in the cavity wall could create an actively driven density differential that could influence convection within the interior cavity.

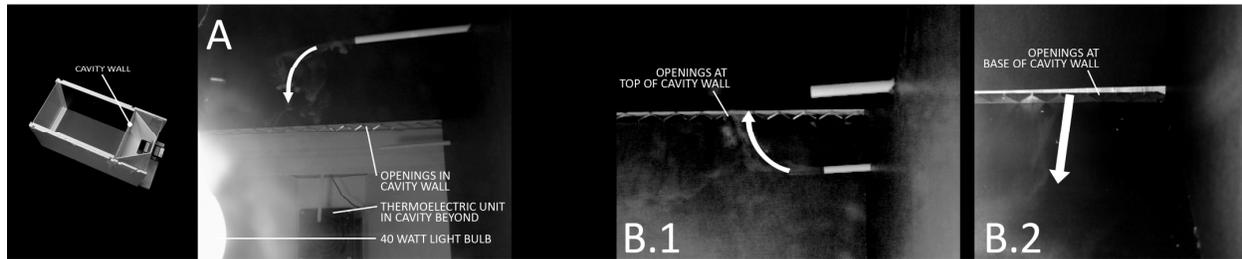


Figure 8: Test using titanium tetrachloride ‘smoke’. When TE unit was off and cavity temperatures were equal to interior, smoke tended to drop, hover, or be drawn towards heat source in interior (image A). With TE unit running (although with interior heat sink fan disconnected to prevent turbulence) smoke was drawn into cavity at top (image B.1) and discharged from cavity at the base (image B.2).

2.3 Towards the Active Thermal Manifold

With the active thermal manifold’s effect demonstrated at a small scale, the research hypothesized that the actively driven differentials in the manifold system could be enhanced as a result of geometry. The development of a performatively-based geometric scheme for creating manifold cells was not available during the most recent academic semester; however, the concept of thermal resistance within the manifold cells informed the development of the current system served in an empirical manner.

Heat dissipation or exchange is related directly to resistance within the transferring medium: this resistance is quantified for heat sinks as the Heat Sink Resistance (or HSR), and this resistance value relates directly to the “rate of heat dissipation from the heat sink” [19]

It may be conjectured that the air volume with the manifold cells, in relating to heat dissipation, performs according to its own resistance criteria. We can consider the equation approximating thermal resistance by convection:

$$R_{CONV} = \frac{1}{h_{CONV} \times A_{SURF}}$$

The first assumptions for the manifold cavities were that vertical divisions or tubes were acceptable – a tube, in this case, would have consistent resistance because both its cross section and ‘h’ provided in the above equation are constant.

Deviating from the geometry of tubes and extrusions, a few examples from nature were observed, concluding that when air or fluid is being moved against the cross section of a channel, this cross section tends to taper. This may be attributed to aerodynamics, but perhaps this is something else. In the context of our problem with resistance, it can be asserted that such tapering cross section serves to change the resistance of an air or fluid channel along its flow path [19]. Changing resistance within the manifold cell would serve two purposes: to place the TE unit in the location of least resistance (the widest part in width and depth) and to increase velocity at the openings where the cell would exchange air with the adjacent space. The latter would occur as a result of the air displacement within the large, low-resistance volume flowing downwards and accelerating as the cavity narrows towards the opening. While this phenomenon is yet to be explored with computational fluid dynamics simulation, these tapering manifold cells were adopted for the final active thermal manifold prototypes.

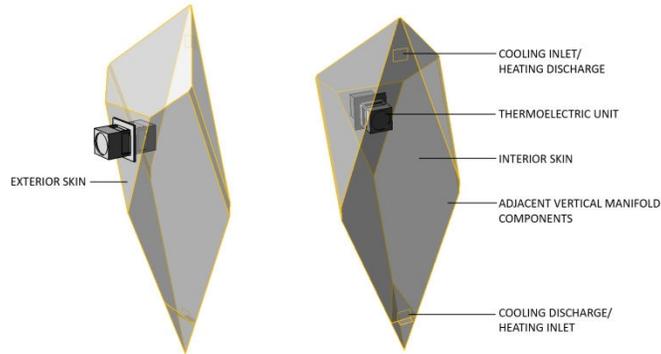


Figure 9: Final geometry of the manifold cell showing tapering at top and bottom related to thermal resistance of the air volume – coincidentally, this approach also helped in ‘packing’ the cells into the wall at an increased density.

3 Current Research

3.1 Proposed Experimental Methods

The objective of the proposed research is to explore and evaluate full-scale prototypes in which functioning TE modules have been integrated into an active thermal manifold prototype. The research, as proposed, has involved the construction of two identical enclosures of approximately 6’x6’x8’, built on wheels, both of which is outfitted with a full-size segment of active thermal manifold wall.

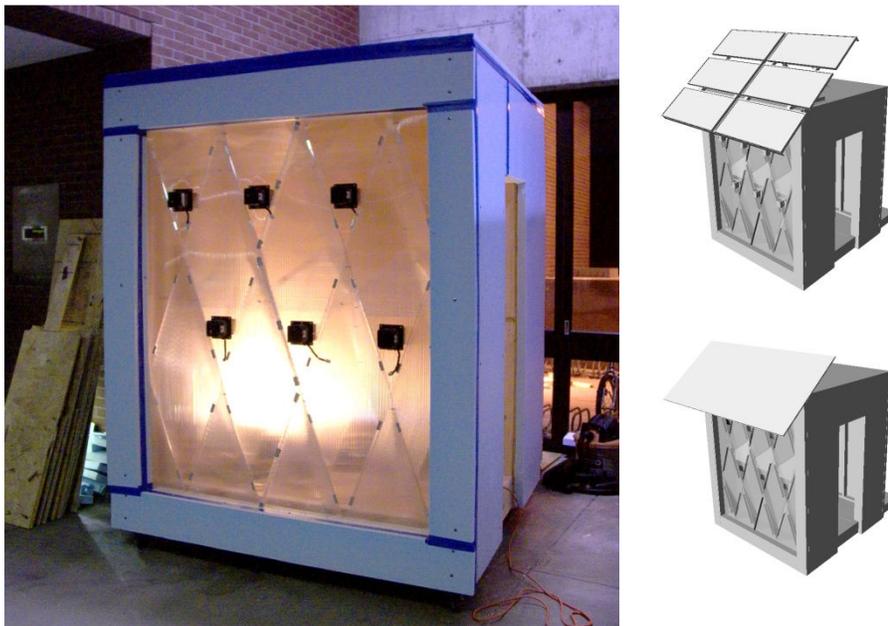


Figure 10 (L): Prototype with completed manifold system and six TE units.

Figure 11 (R): Representation of the two identical prototypes that will be used in experimentation. The prototype on the top is the active prototype, outfitted with PV’s and TE units; the prototype on the bottom is the passive prototype, using the same manifold system but without TE units. A sheet of plywood will be used to provide the equivalent shading that the PV panels provide in the active unit. Performance differences may be directly attributed to the TE’s during experimentation.

The primary experimental method will be to outfit one of these enclosures with a photovoltaic-powered TE module array. The other enclosure will be similarly shaded, but will have no active systems installed. The consequence of this experimental method is that both prototypes (the active and non-active) can be tested under real environmental conditions and subsequently compared. A variety of instrumentation (some that have been used in previous trials discussed in this report) will be used to collect data from the prototypes, and the two sets of data will then be statistically compared.

Cooling and heating capacities of the prototype TE system will be calculated, based on comparison with the passive load. The following equation will be used to estimate the passive load encountered in the prototypes: [20]

$$Q = \frac{P \times \Delta T_{DES}}{T_{AMB} - T_{ENC}}$$

Where:

Q is the passive load, expressed in watts;

T_{AMB} is the ambient temperature after stabilization (in C°);

T_{ENC} is the enclosure temperature after stabilization (in C°);

ΔT_{DES} is the desired temperature difference between the inside of the enclosure and the ambient environment (in C°); and

P is the power dissipation within the heater employed for the test (expressed in watts).

In general, the prototypes will serve as the primary experimental tool: however, parallel explorations will be conducted using computational fluid dynamics modeling, which can be used to test variations in manifold geometry and scale [21]. The objective of this activity will be to better determine the relationship between the geometry, air flows, and TE performance.

It may be important to note some of the differences between this research and that of the ABE presented by Van Dessel. The ABE prototype used natural convection for internal and external heat dissipation, the researchers performance-optimized the power supplies for their specific modules, and the TE modules were a relatively low-capacity module. Additionally, Van Dessel's experimental method evaluated the success of heating and cooling using a statistically-based approach that compared a series of 'on' and 'off' days. With only one prototype for collecting data, this research team needed a large sampling of data to reach a statistically sound result. Lastly, it seemed this experiment had not openly addressed air flow or a defined strategy on how the 'active' element in the system would influence the interior cavity, although these observations may not have been presented. [22]

In contrast, this experiment is using full size prototypes in which patterns such as air circulation can be observed in real life, as well as impact internal temperatures in a realistic manner. The TE units are larger units which can (and have) produced a substantial temperature differential. And lastly, if the two prototypes have deviating internal temperature curves, it may be concluded that the TE devices are pumping heat effectively.

3.2 Construction of the Prototypes

When the concept of partitioning the double skin cavity emerged, a particular fabrication problem emerged with it: how to build a full three-dimensional lattice of folded components and join this internal lattice with inner and outer skin layers. Glass was ruled out because of the difficulty in joining component and because of its low thermal resistance. For the purposes of the prototypes, plastic was pursued as a good candidate because it could be easily formed and connected. The final material selection was 8mm multi-walled polycarbonate, typically used for greenhouses, hurricane-proofing, and economically constructed atria and skylights.

Polycarbonate, due to its multiwall construction has a high thermal resistance ($U = 0.5 \text{ W/m}^2 \text{ }^\circ\text{K}$). Creating the manifold from this material would keep the cells as isolated as possible from each other. Solar gains from the outer layers of the skin would be prevented from reaching the manifold cells with the TE units, and the TE units cooling load would be focused on the air in the manifold as much as possible, rather than gains conducting through the cavity walls.

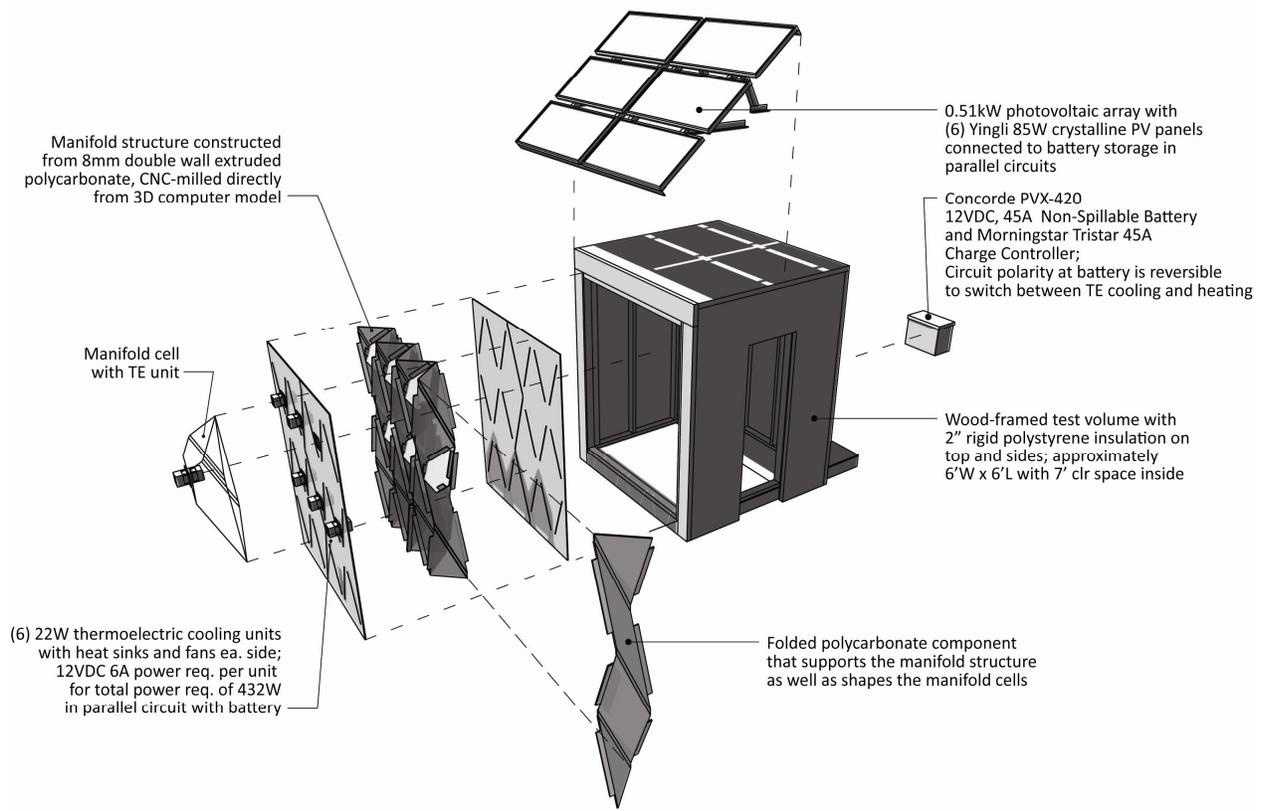


Figure 12: Diagram of prototype construction showing the various components. Note that blocking and additional insulation used to seal the perimeter of the manifold structure is not shown in this image.

The plastic construction would also satisfy the dual objective of the manifold skin as a daylighting membrane, in the spirit of other projects in which high tech plastics which can do double duty as daylighting system, insulating skin, and technological armature. Kieren and Timberlake's development of the SmartWrap system using integrated lighting and photovoltaic cells is part of this group of recent plastic projects, as well as a handful of projects designed by Shigeru Ban – one of which, called the Naked House, employs double-skin plastic walls.

Designed with the extensive use of computer-based 3D modeling, the manifold system employed in the prototype consists of an inner and outer membrane with a series of folded internal walls. Internal walls come together in an alternating lattice pattern to form diamond-shaped cells, some of which house the TE units. Together with the TE units, these create the six 'active' cells within the manifold, and have a three-dimensional form that tapers at the top (intake) and the bottom (discharge). As discussed earlier, such geometry is devised to establish air resistance differentials, which is hypothesized to increase the effect of density differentiation within the manifold. Polycarbonate sheets with CNC milled by the author using a Thermowood 3-axis CNC router mill which is part of IDF and the College of Architecture and Planning.

The manifold system as a complete structure is 10 5/8" in depth and comprises a total volume of 51,364 cu.in. The 'active' cells in the final design have a volume of only 3,141 cu.in. to comprise a total of 18,846 cu. in. for the six active cells. The percentage of active cell volume to the total manifold volume is 37%...providing the TE units a more manageable heating and cooling load. The important aspect about this geometry is that the active cells comprise a mere 8% of the direct exposure to the exterior, but on their opposite side comprise 55% of the interior exposure. This positions the active cells in the best position to function as a thermal buffer while allowing the TE devices to focus work on cooling and heating that cycle.

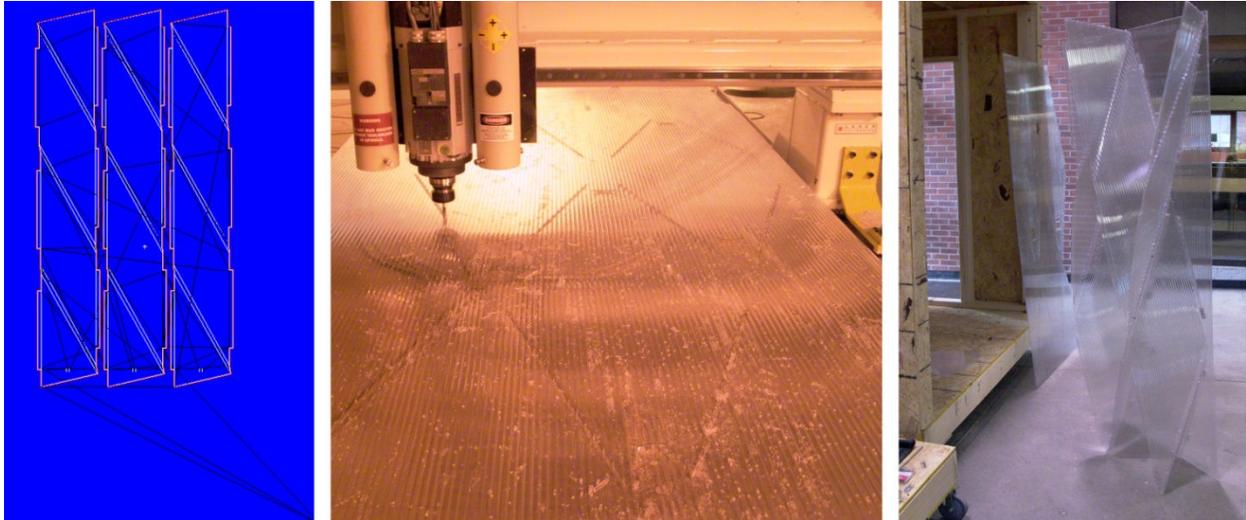


Figure 13: Computer modeling and CNC fabrication was employed to design and produce the manifold. Fabrication was completed in-house using college/institute resources

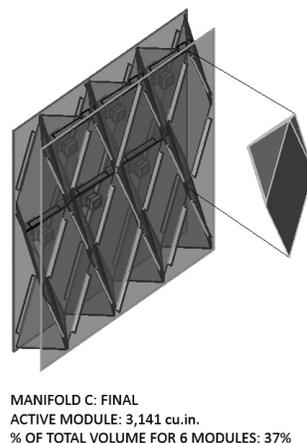


Figure 14: Relationship of manifold cell to overall structure

The framing of the prototypes is composed of conventional 2x4 and 2x6 construction, covered with ½” OSB sheathing (walls) or 5/8” OSB sheathing (floor and roof) and then finally insulated with 2” polystyrene rigid insulation, which was both adhered and mechanically fastened. Seams and gaps in the insulation layer were masked with high strength tape, in lieu of Tyvek or a similar product which could prevent infiltration.

3.3 Final Thermoelectric and Photovoltaic Specifications

Six Tellurex A22 TE coolers were selected for the current prototype – each cooler provides approximately 22W of cooling capacity and requires a power supply of 6A at 12V. The total cooling capacity of the TE system is 132W and the total required power supply is 432W.

The chosen photovoltaic system is battery-based. During the assembly of the original desktop prototype, the photovoltaic system was based around a high-efficiency (over 90%) DC to DC convertor, rather than a battery. This device operates by converting input power from the photovoltaic panel (generally stable current but varying voltage dependent on cloud cover, panel temperature, etc.) into a nominal output of 12V required by the TE device. Fluctuations in the PV power supply would be changed by the convertor into fluctuating current, which TE devices generally tolerate. The DC to DC convertor was intended to allow a direct connection from the PV panel to the TE module, which without it would be potentially dangerous to the TE as a result of the higher operating voltages

presented by PV's (18V or more, which is useful for the battery-charging most systems are designed to do). The hope of such a system would be a seemingly discreet pairing of PV to TE device that could be duplicated along the building skin. However, the DC to DC convertor never succeeded in completing a circuit between a photovoltaic panel and a TE device. It was learned that photovoltaic electrical circuits start out with an effective current of zero until an electrical load is added to the circuit (the open circuit rating which is the highest voltage outputted by the PV, is coincidentally a zero on the typical PV performance curve). Conventional circuitry within devices such as DC to DC convertors, which are intended for use in micro-controlled devices, have built-in switches that will only turn on the device if a current is detected. Thus the range of typical DC to DC convertors could not be used for the experiment and instead a battery based system is used. Here, the battery will lower voltage in way similar to a DC to DC convertor.

The final battery-based system [23] is built around a single 12V, 45A-rated battery. Connections to the battery from each TE module will be parallel circuits, with each TE module operating with the nominal 12V output from the battery and the battery's 45A output divided among the six modules. The PV array will consist of six 85W panels manufactured by Yingli Solar (China); the panels are crystalline-cell type, which should maintain relatively high outputs even during overcast days. The array is sized to produce a rated output of 510W, and has a derating factor of 85% matched to the power supply required by the TE modules. A charge controller is the final addition to the system, which will modulate the total power output of the PV array to optimize battery charging.

3.4 Initial Findings

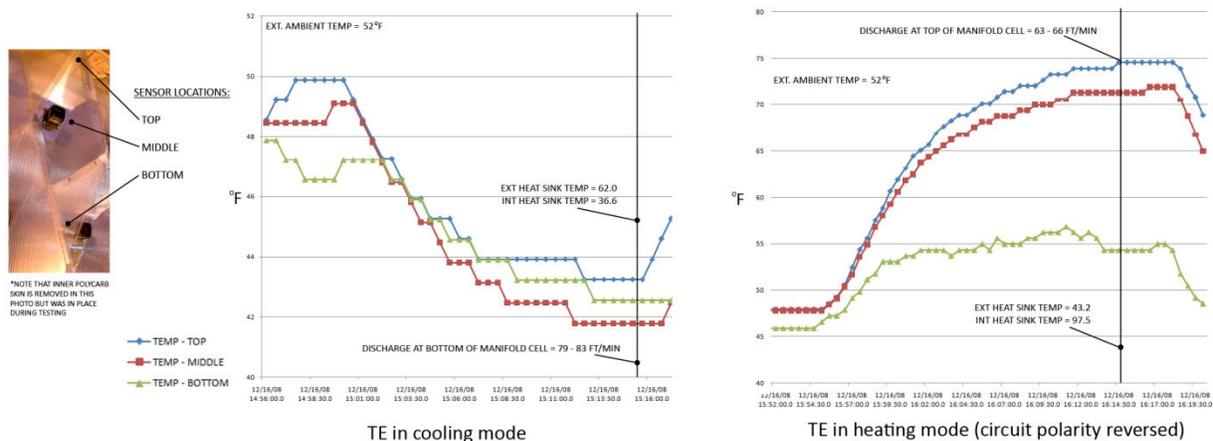


Figure 15: Results from a preliminary test of a single manifold unit cooled/heated by a single TE unit. Note that the testing conditions were not ideal for cooling due to the location of the prototypes (an unconditioned space in a northern climate). Stow-Away XTI sensors positioned at top, middle, and bottom of the manifold cell and for each test the TE unit was run for 20 minutes. The manifold, under active cooling/heating from the TE, was expected to create internal temperature differentials that could be observed both in the stratification of interior cavity air temperature as well as with discharge/intake at the extreme ends of the manifold. Results from this test are very positive – although the insulating properties of the polycarbonate seemed to have trapped some cold air, prior to the experiment, since all temperature values in the cavity were initially lower than ambient. Heating was especially successful – with discharge air reaching nearly 75 degrees (over 20 degrees increase from ambient temps) and clear organization within the cavity of air temperatures. Cooling demonstrated less organization in internal air temps as cooled air apparently warmed up slightly as it dropped – however, this could be related to the asymmetrical vertical geometry of the cells and discharge air at around 43 degrees was a 10 degree drop from ambient. Discharge rates were measured with the impeller of a Kestrel 4000 hand held weather station. Later tests will use a hot wire anemometer to achieve more accurate results.

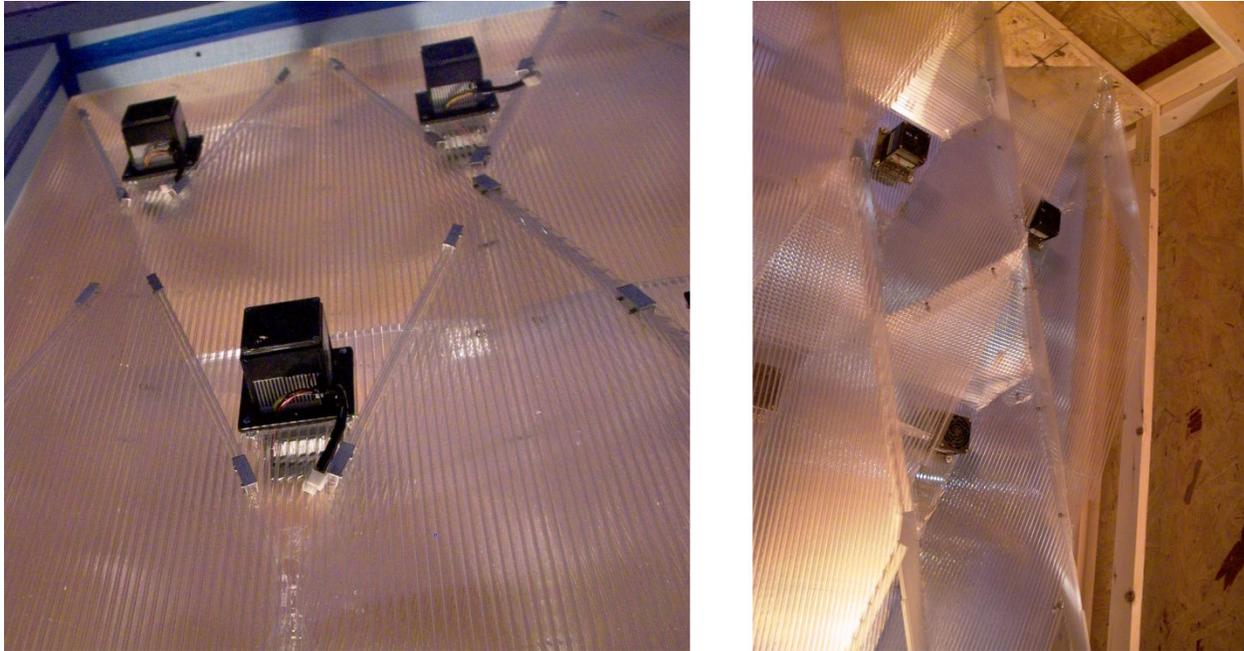


Figure 16: Active thermal manifold wall during construction, showing external and internal details. Continuing experimentation with the system in real life and using computer simulation is expected to reveal a more complete understanding of how the ‘active’ aspects of the system are reinforced by the geometry of the construction.

4 Conclusion: Expected Relevant Outcomes and Future Research Trajectory

As this research evolves, the prototypes will become the subject of several smaller explorations that will include the following: creating a parametric digital model of the structure to understand how the geometry can respond to architectural conditions, experimenting with natural convection (no fans) on either side of the devices in the prototype, evaluation of a single heat-dissipating fin plate compared with the heat sink, and the development of a microprocessor control strategy for controlling the impact of the TE’s on air circulation patterns.

However, the critical next steps involved in this research begin with thorough real-world testing of the constructed prototypes. This is planned first for cold weather and later for hot weather. Aspects of the prototype’s performance will be observed for the first time at this scale – informing, particularly, how successful the relationship between the manifold’s geometry and the TE system performs. Because the manifold geometry will be duplicated in a second, non ‘active’ prototype, the real world performance results of the ‘active’ system can be observed. Working with both computer-based simulation tools and prototype modifications, the research will hopefully demonstrate the independent performance implications of geometry, TE distribution and scale, and photovoltaic power supply on the interior environment – yet moving towards a result which can optimize these conditions into a viable demonstration of an active manifold wall system.

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- [23] Xu, xu *ibid* p168-174
- [24] This system, included photovoltaic panels, had not shipped in time to be added to the prototype before the submission of this report.

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