Chapter 12
Aesthetics and Perception: Dynamic Facade Design with Programmable Materials

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Abstract Technology is often defined as the application of science to solve pragmatic human problems. Etymologically, the roots of technology are closely related to artful and skillful, and entwined with the idea of beauty. Much of technology teaching and professional architectural practice focus the former definition, with emphasis on energy reduction, measurement and building physics. While technical building metrics are important, they often overshadow the prospect for building technology to appeal to the imagination, engage the senses, and support emotive human connection with the environment. In fact, most building technology is designed to separate us from the environment. Smart materials, those which adjust their properties according to environmental stimulus, have the potential to physically index subtle changes in the environment, generating human awareness of environmental flux. It is proposed that by integrating the properties of smart materials within the façade and interior building surfaces, building technology can become a dynamic link between environmental changes and human sensory experience. Design experiments that expand the thermal and aesthetic properties of dynamic facades, with phase change materials and shape memory polymers, are presented.

Keywords Building performance · Aesthetics · Shape memory materials · Programmable matter · Architecture

12.1 Introduction

It's easy to fixate on technology. Especially if we are working toward a goal with quantifiable metrics, such as computing thermal transfer through a given wall section. Often these metrics become primary drivers in the early stages of the design process and significantly influence, the form and aesthetics of a building, and by extension, all those that come into contact with the building. While there is no single definition of building performance, the quest for performance increasingly impacts the design

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of the built environment through an ever-widening array of simulation tools targeted to optimize flows of heat, light, sound, air, and information. As such, the building envelope has become a locus for innovation, and a shift from viewing the façade as a wrapper to a medium of exchange between interior and exterior. Architects and engineers are beginning to apply computational tools, emergent materials, and a host of sensing and actuation technology, not just in service of building science, but to advance the role of the sensorial and qualitative aspects of building technology and search for ways that buildings can communicate their operation to building inhabitants.

A position is taken that the built environment can and should more effectively respond to nuances in local environmental conditions and that humans should be aware of how a building adapts in real time. Adaptive technology is becoming more prevalent as the building industry shifts from relatively static materials such as glass and steel, to dynamic materials that exist in multiple equilibrium states or non-equilibrium states and can respond autonomously to their environment. Still in their emergent stages, programmable materials, when applied to the building envelope, have the potential to lower the complexity of dynamic and responsive envelope systems by consolidating the sensing and actuation systems that more mechanical dynamic systems require to operate.

Two projects are presented that bridge material science and architecture through the application of programmable materials. The projects contribute to the current trajectory of work that challenges the notion of fixity in the design and operation of buildings, in favor of relatively simple means of dynamic environmental response. Each project has technological roots in programmable matter, but the architectural applications are consciously low-tech. The projects are intended to lower energy consumption by actively responding to fluctuating environmental conditions, but importantly, they are intended tap into the human need to be connected to the environment. Design examples are given of recent work with an emerging class of organic phase change materials (PCMs) and with shape memory polymers (SMPs) that demonstrate the prospect of dynamic materials to make architecture more thermally and visually responsive to local temperature variation.

12.2 Engaging the Senses

In Thermal Delight in Architecture, Lisa Heschong gives a compelling history of cultural development through human engagement with thermal sources. She speaks to the sensory engagement and human connection that occur through direct contact from thermal sources. Whether a group of humans are immersed in a thermal bath or sitting in a circle around a fire, Heschong proposes that we gather around thermal sources to satisfy our physical need to warm ourselves, our emotive need to be physically engaged, and our cultural need to exchange ideas and tell stories.

Heschong's book is informational and not as immediately apocalyptic as Rachel Carson's truth-based fable Silent Spring, but it carries a foreboding message in terms of blind reliance on technology. Specifically, Heschong warns of the cultural damage brought about by the designed and progressive separation of humans from nuances in the environment. She insinuates that we care less for our surroundings if we are disassociated from them. In thermal terms, if we do not know where the heat in a building is coming from or how it is produced, this lack of connection can beget carelessness. It is arguable that social and sensorial impoverishment can result from environmental detachment, leading to a coarseness with which we relate to our surroundings. As we are sensing creatures, once our physiological response to the environment is stunted, so too is our cognitive awareness. Heschong does not advocate a return to the campfire but is in favor of building technology that enhances social interaction by engaging the user sensorially and emotively. While contemporary building technology is the result of thought, engineering, and skill, in general, it is designed to detach the user from the operation of a building, in favor of semi-autonomous control systems that are often acoustically masked and hidden from view. This following work is part of a resurgence of projects that seek to make environmental technology both visual and visceral.

12.3 Keeping the Good Stuff in and the Bad Stuff Out

Buildings are often designed as a static barrier condition, isolating inhabitants from the environment. This approach approximates that tactic of a latex glove; a strategy designed to keep the good stuff in and the bad stuff out. In the case of buildings, the bad stuff is the environment, even though studies have shown that interior air quality often contains significantly more pollutants than exterior air (U.S. Environmental Protection Agency 1987). This is a concern as the global population is becoming domesticized and spends an increasing amount of time indoors (Wallace, 1987). Intuitively, we know that connection with the environment has been fundamental to our evolution and is central to our physiological and psychological health. Though there is little professional agreement on what connotates good design, researchers have studied the direct and indirect effects of buildings on human health, psyche, and well-being (Evans, 2003). Designers are also beginning to challenge the practice of defaulting to highly insulated air-tight buildings in favor of responsive and dynamic building envelopes that are meet the needs of occupants by adjusting to the environment.

Researchers and practitioners have proven Winston Churchill's observation that "We shape our buildings; thereafter they shape us." R.A. Ulrich, a researcher of evidenced-based health care design, has provided a direct link between design and well-being through study of the acoustic and visual environment on patient stress, anxiety, and recuperation times. In one project, Ulrich studied patient reports from a Pennsylvania hospital, where rooms on a double loaded corridor either had unobstructed views of a stand of trees, or a view of a monotonous brown brick wall. He found that the patients with a view received fewer negative evaluative comments, required less pain medication, and were released earlier, than those subject to the monotony of a brick wall (Ulrich, 1984). Many other studies have shown that increasing occupant awareness of variations in daylight levels within buildings leads to better and longer sleep patterns, positive mood effects, and increased cognitive functioning (Boubekri et al., 2020).

The projects that follow focus on the prospect for architecture to continually attune itself to its surroundings, and visually index thermal environmental change through variations in opacity and surface texture. The objective is to apply the attributes of programmable materials to combine aesthetics and performance, thereby recoding our relationship with the environment through the variability of the building envelope.

12.4 Project 1_ Phase Change Materials

Architectural materials are generally static and designed for stability and durability. Responsive materials, also known as reactive or 'smart' materials, vary their properties in response to external stimuli. These materials are controllable and reversable, and some are programmable. A common property of these materials is that sensing and actuation are embedded withing the material itself, lowering mechanical complexity in comparison to dynamic systems that rely on external sensors and actuation methods. PCMs and SMPs are part of an emerging class of responsive materials with programmable properties that can be tailored to trigger or switch in response to specific environmental stimuli such as magnetism, light, temperature, or humidity.

It makes all the sense in the world to use mass, as opposed to air, to moderate temperature in buildings. Massive materials have long been used to store or release energy to mediate diurnal temperature swings. Historically, these materials have functioned as sensible heat storage (SHS) systems that proportionally absorb or release heat according to increasing or decreasing temperatures. This approach, used in Trombe walls and concrete slabs exposed to the sun, comprise effective and uncomplicated thermal storage banks, though a lot of material is required to stabilize internal temperatures. In SHS systems, thermal storage capacity generally increases with density. Unlike conventional SHS materials, however, when PCMs reach the temperature at which they change phase, referred to as their set point, they absorb or release large amounts of energy and maintain an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around the liquid PCM falls, the PCM solidifies, releasing its stored latent heat, as depicted in Fig. 12.1. Water, the PCM we are most familiar with, changes phase (liquid/solid) at 0C. As liquid water crystalizes, it takes on a more ordered structure and absorbs energy from the surrounding environment. As solid water melts, it assumes a less energetic state and releases energy. The reverse is true as water freezes, making water a highly effective thermal storage material as the material changes phase. In both cases, the material maintains a near constant temperature as it proceeds through phase transition. This property is especially useful in moderating temperature swings, whether in buildings or a cold glass of water. Organic PCMs, such as the soybean oil used in this study, operate with the same principle, though the melt/freeze point can be targeted to ambient room temperatures, making the organic oils effective materials for thermal stabilization in buildings.

PCMs in building technology are generally micro-encapsulated or macro-encapsulated. The process of micro-encapsulation entails enclosing phase change particles within a polymer shell. The shell effectively contains the PCM core through its freeze-melt cycles. Micro-encapsulated PCM can be added to building products such as plaster, drywall, concrete, or composite roofing systems to increase their thermal storage capacity. PCMs generally exhibit low thermal conductivity, and micro-encapsulation is a step towards overcoming this limitation. Macro-encapsulation refers to enclosing substantial amounts of PCM within a single container, a process that is becoming more technically and economically feasible with the emergence of organic PCM. Organic materials are generally preferred as they exhibit lower corrosive properties than inorganic salts or metallic compounds, making container composition less exacting and container degradation less of an issue. These properties open the door for more creative and effective packaging solutions. The following projects encapsulate PCM in containers that augment the thermodynamic attributes of the material and to make the phenomena of phase change visible.

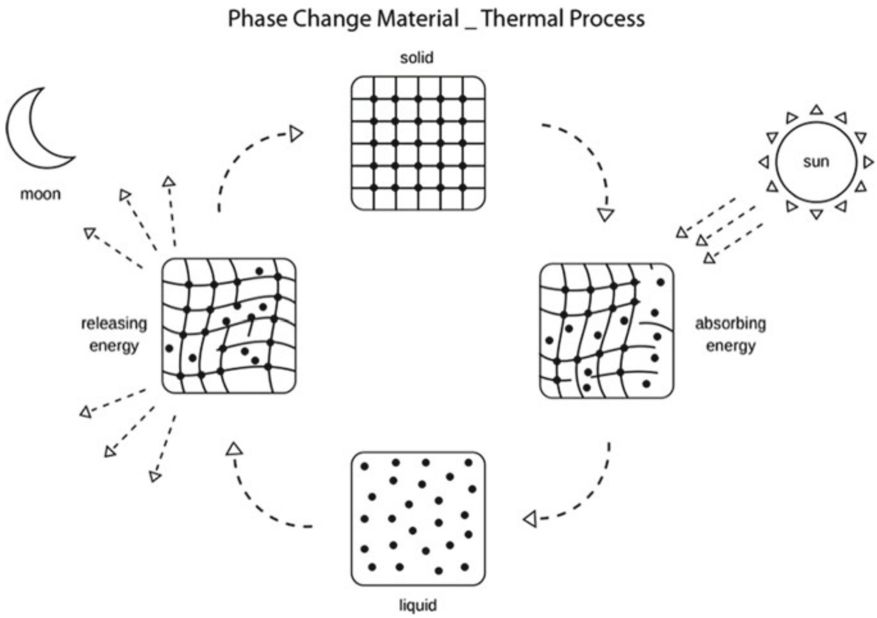

Fig. 12.1 Phase change cycle. This figure shows the cyclical thermal process of a phase change material beginning in a solid state, liquifying as energy is absorbed, then returning to a solid state as energy is released

12.4.1 Rethinking PCM Placement and Operation

Commercially available PCMs are most often packaged in opaque plastic and located above acoustic ceiling tiles or behind drywall. In these locations, the material mitigates internal temperature fluctuations, but it remains hidden from view. The ‘Tile’ project is an effort to rethink the placement of PCM within a building and the existing methods of packaging to better promote the conduction of thermal energy between the phase change material and the surrounding air and to visually exhibit the freeze/melt transitions to building users. The soybean oil used in this study has relatively low thermal conductivity (0.2 W/m/K) and tile designs with a high ratio of PCM to container surface were made to manage this issue. The first series of tiles (Fig. 12.2) are constructed from thin glass with an interlayer of PCM. The high surface area of the container accelerates the transfer of heat between the environment and PCM. The transparent nature of the tile also exhibits the crystalline structure of the oil as it solidifies and absorbs energy from the surrounding environment. The oil varies optically from opaque when frozen to near clear when melted.

It was observed that the tile acted as a temperature dependent optical switch, registering the thermal condition where the tiles were located. To a building user, the tiles index the relationship between the optical aspects of material change and the thermodynamic conditions of a given space. The tiles are designed to make

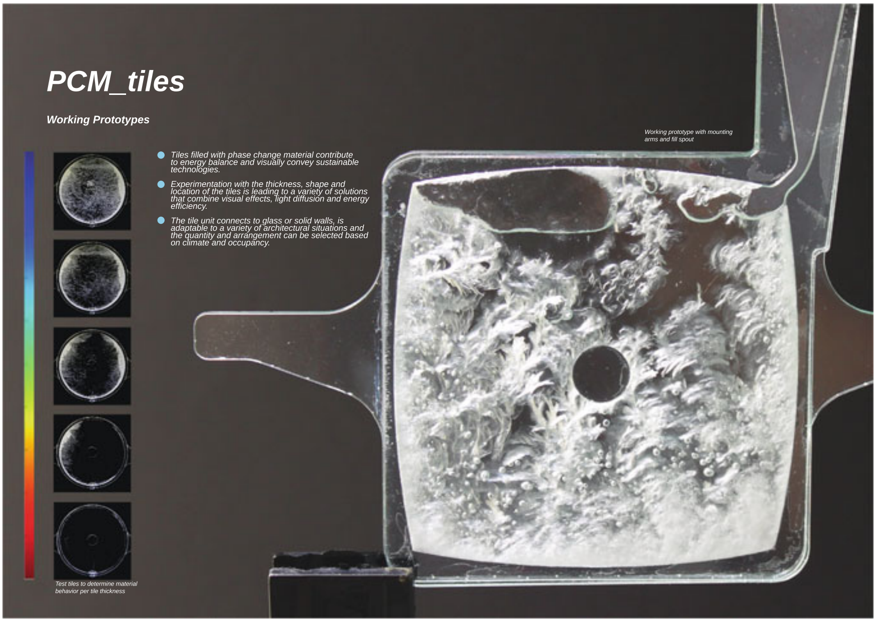

Fig. 12.2 PCM tile. This figure shows the encapsulation of PCM within a glass container. The fill tube and expansion chamber are seen at the upper right of the tile. The images at left demonstrate the spectrum of material opacity, from near clear to opaque, during the freeze/melt cycle

invisible temperature changes visible and alter one's perception of a building as a static entity, in favor of recognizing the energetic exchange between interior and exterior conditions. The intent of the project is to change the way buildings are experienced by communicating through its operations.

12.4.2 Application_ Expanded Wall Section

The tiles were assembled into an array that expanded the 'space' of the façade as they are located directly adjacent to the interior of the glass surface. This zone undergoes significant diurnal temperature swings, and the placement of tiles enables the façade to serve as a thermal storage bank and heat recovery system. Arrayed vertically and horizontally, a thermal bank of 360 tiles was designed to help the Frick Park Environmental Center, in Pittsburgh, PA meet the energy petal of the Living Building Challenge and to explore the communicative potential of sustainable technology (Fig. 12.3). Early energy analyses showed that total building energy consumption would be reduced by 25% with the PCM system proposed.

The following iterations of the PCM tile depart from the planar container and are shaped to increase the volume of PCM per tile and to increase the velocity of airflow across the container surface (Figs. 12.4 and 12.5). The design intent is to increase the effectiveness and the thermal storage capacity of the system by increasing the convective heat transfer to the surrounding air (Clifford et al., 2017). The thermo-formed container is filled with PCM with a variety of set points, to further enhance the reading of the interior facade's response to temperature variation.

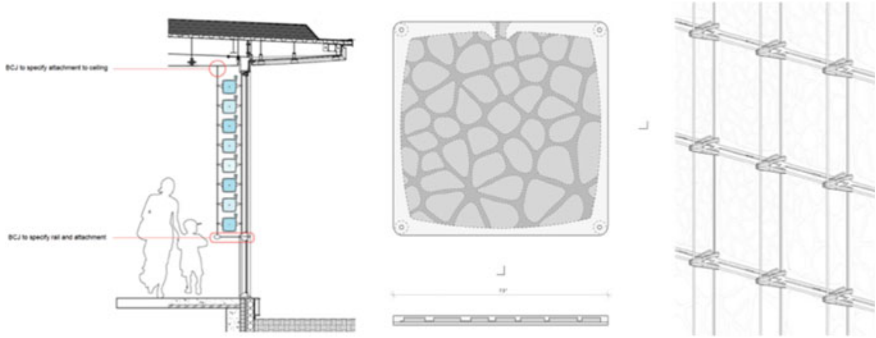

Fig. 12.3 PCM tile application**.** The image at left shows the placement of the PCM tile array perpendicular to the interior of a glass façade as designed for the Frick Park Environmental Center, Pittsburgh, PA. The image at right is a test for a multi-cellular PCM tile and an installation system that places the tile parallel to the glass façade

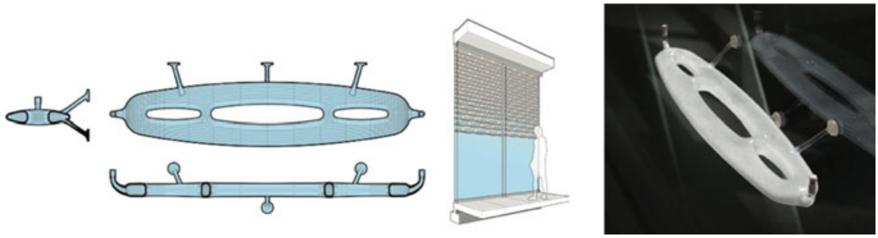

Fig. 12.4 Increasing Airflow. The image at left is a drawing for a PCM filled container designed to increase airflow when arranged in a field (center image) on the interior of a glass façade. The image at right shows a prototype module filled with frozen soy oil based PCM

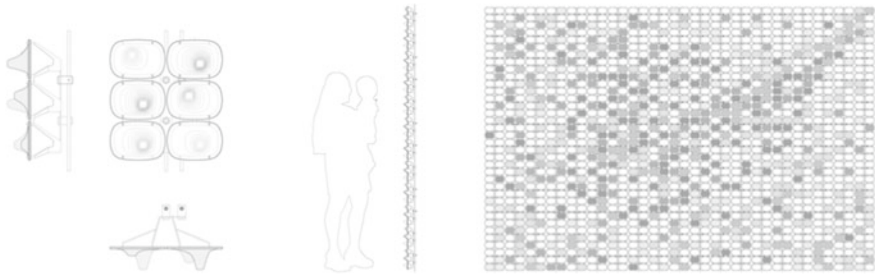

Fig. 12.5 PCM Tile Array. The drawing at left shows a plan and elevation of a PCM containment system that clips onto vertical cables. Three container types were designed with different surface curvature and volumes. The image at right shows the PCM wall system with tiles in different stages of their freeze/melt cycle due to volumetric difference of the tile. The thermal operation of the system is registered in the patterns of translucency

12.5 Project 2_ Shape Memory Polymers

Continuing the intent to enable the façade to adjust to thermal fluctuation in the local environment, this project applies the properties of shape memory polymers to vary the façade surface area and texture. The shape memory polymer tile developed, predictably varies its shape in response to heat and applied air pressure. Operating as a field, the tiles form an articulated surface designed to reduce the transmission of solar radiation through adaptive shading. The tile system is designed to respond to multiple solar insolation states rather than a single optimized state. A secondary goal is to develop a computational design tool capable of determining the local mechanical actuation and thermal activation mechanisms to morph the tile into a shape that maximizes the desired solar-tile interaction with minimal total morphing energy cost. Initial physical models are presented that incorporate knowledge exchange between partners at the University of Pittsburgh that specialize in applied computational mechanics, researchers from the University of Dayton Research Institute with expertise in materials science, and a team from the Cal Poly Department of Architecture that specializes in design process.

12.5.1 Shape Memory Effect

Shape memory refers to a class of materials that can be deformed and then recover to its previous shape when subject to stimuli. Shape memory effect was coined from the study of alloys and was first observed in the 1930's. Shape memory research with synthetic resins dates to 1941 and is attributed to a patent issued to Vernon et al. (1941) who developed a thermoplastic that exhibited elastic memory when heated. Vernon's discovery introduced a body of research into shape memory materials and shape memory effects. Most shape memory research has been with metals, known as shape memory alloys (SMAs) and shape memory polymers, although less studied. A wide variety of organic materials such as wood (Zhang et al., 2021), hair (Wortmann et al., 2021), and collagen also exhibit shape memory properties. Among the shape memory materials under development, SMPs have characteristics that are particularly applicable to building technology and differ from their alloy counterparts as they have a lower density, exert less force upon recovery, and can undergo significantly higher strains. Polymers can be designed to respond to a range of stimuli, including, light, electricity, magnetism, moisture, and ph, but the most studied stimulus is heat. Other desirable properties of SMPs include that they are programmable, exhibit variable stiffness, undergo large recoverable deformation without fatigue damage, and require minimal actuation force to change shape. They also possess good shape fixity and have a relatively low time to recover to their programmed shape (Kang et al., 2018).

12.5.2 Temperature Activated Shape Memory Polymers

The SMP used in this study is a temperature activated polyurethane polymer that can be programmed to attain a single, yet reversible, programmed shape. Above its glass transition temperature (Tg), the polymer softens and can be easily deformed. If cooled, the material stiffens, holding the deformed shape. Upon reheating above the Tg, the material will assume it's programmed shape which is set into the material upon fabrication. The programmed memory shape is achieved either through casting or printing, for example, if a tile with a curved surface is printed, and deformed, the tile will recover to the printed shape upon heating. In our experiments the polymer reached a limit and could undergo the strain of approximately 200% before rupturing, which set a range of maximum surface areas to work within. Temperature activated polymers were used in this study due to their availability and relative ease of fabrication technique. To deform the tiles, heat was applied externally with a heat gun, a significant source of external energy. If the tiles were intended for production, a more ideal SMP would be a light activated polymer which has been shown to use far less energy for activation. Another possibility is to tune the Tg of the polymer more closely to the ambient air temperatures hot environments, thus decreasing the energy cost of activation. In some design iterations, dark mass was applied to the polymer surface to concentrate heat in targeted areas. And further options include

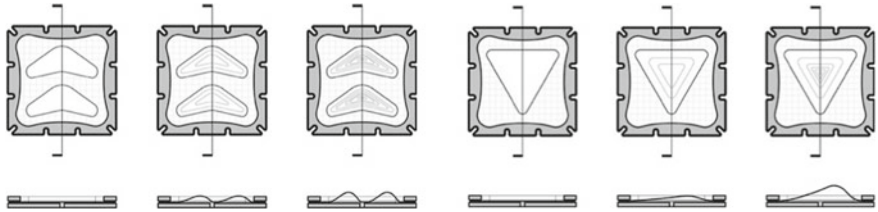

Fig. 12.6 Composite tiles. Variable stiffness composite tiles made from shape memory polymer and ABS plastic showing sequential actuation. Tiles were heated just above the glass transition temperature with constant air pressure. The lower series of drawings indicate the deformed tile shape

the application of multi-stimuli-responsive shape memory polymers programmed to respond to both heat and light.

Two fabrication techniques were used to better understand the dynamic qualities of SMP's, with an end goal of fabrication consistency and gaining predictive control of the deformed state of the tile. The first series of tiles (Fig. 12.6) were cast from a two-part resin with a Tg of 25C with materials purchased from SMP Technologies. They were combined with a stiffer inner material to generate a variable stiffness tile intended to influence overall deformation. The composite tile exhibits variable stiffness as the SMP has a lower elastic modulus than the printed ABS. This effect is pronounced when the tile is heated above the Tg and the polymer enters the plastic state.

The second series of tiles (Fig. 12.7) were made from SMP filament with a Tg of 55C and printed with variable thickness along the cross-section. The tile composed in successive layers oriented 45 degrees from the previous layer forming a cross-laminated tile. Three layers form a 0.06″ base layer and three more layers form a 1.2″ region noted by the shaded area in the drawing and in the more deformed area in the physical model. The thinner regions reach Tg more quickly and thus deformed earlier, exhibiting greater deformation than the thicker region. This experiment gave control over asymmetrical shape generation with even surface heating and constant air pressure. Tiles were arrayed into a larger matrix and air pressure was regulated via a microcontroller to a series of four tiles (Fig. 12.8). Pressure was controlled with a temperature sensor that released air to the tiles when they reach their transition temperature. As noted previously, there is a lot of kits associated with the current experimental setup and the end goal is to rely less on mechanical sensing and actuation devices and more on the inherent responsive properties of the materials.

12.5.3 Applications and Issues

The proposed application is an external shading device activated by air pressure when the Tg is reached. The intended source of heat ideally comes from the sun,

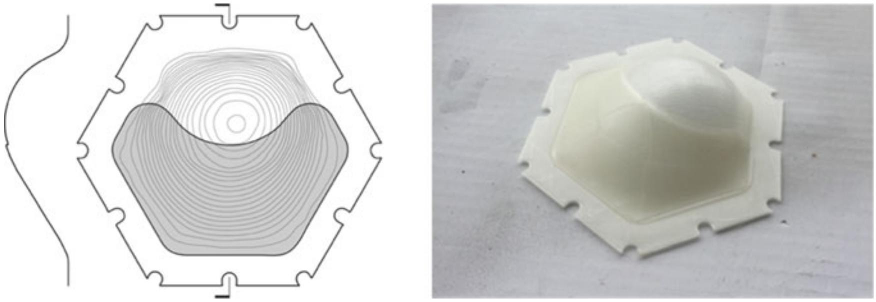

Fig. 12.7 Variable thickness tile. At left is a section elevation drawing of a variable thickness shape memory polymer tile with the shaded region thicker than base thickness. At right is a deformed variable thickness printed tile. Varying the tile thickness gave the team insight into control over tile surface curvature

necessitating a Tg targeted towards specific thermal microclimates. It is anticipated that through selective application of dark mass, the SMP would reach the transition temperature, become plastic and inflate, providing shade to the façade surface. Like shape memory alloys, SMPs require a bias force to reset them to their original preprogrammed shape. This condition requires additional energy input, increasing the cost of operating the system. Energetically, reheating is not viable, and therefore the preferred tile would be composed of light activated polymers.

While two-way shape memory materials are promising in laboratory studies, materials with these properties are not yet commercially available. As described above, the polymer used in this study is a 'one-way' system where a shape is thermally set. Current research teams have produced polymers that can be programmed to attain multiple shape shifting states (Chen et al., 2010). Application of a material with multiple programmed shapes would potentially increase the fidelity of dynamic facades constructed from SMPs and significantly reduce or eliminate the complexity of the actuation system. It is speculated that a façade composed of materials with multiple shape shifting states could operate solely from thermal input from the sun.

12.6 Conclusion

For decades, the directive of environmental control systems in buildings has been directed at human comfort and convenience, and convenience generally meant rendering invisible the systems responsible for internal climate control. An arguable point behind the work presented is that separating humans from the technology that produces comfort has exacerbated our distance from nature, dulled the senses, and by extension, diminished the imagination. This argument supports an expanded definition of building performance to include cognitive, emotive, and communicative aspects of design. This is an old idea, as buildings have long had the ability to communicate to their people through their form, and in some cases, their operation.

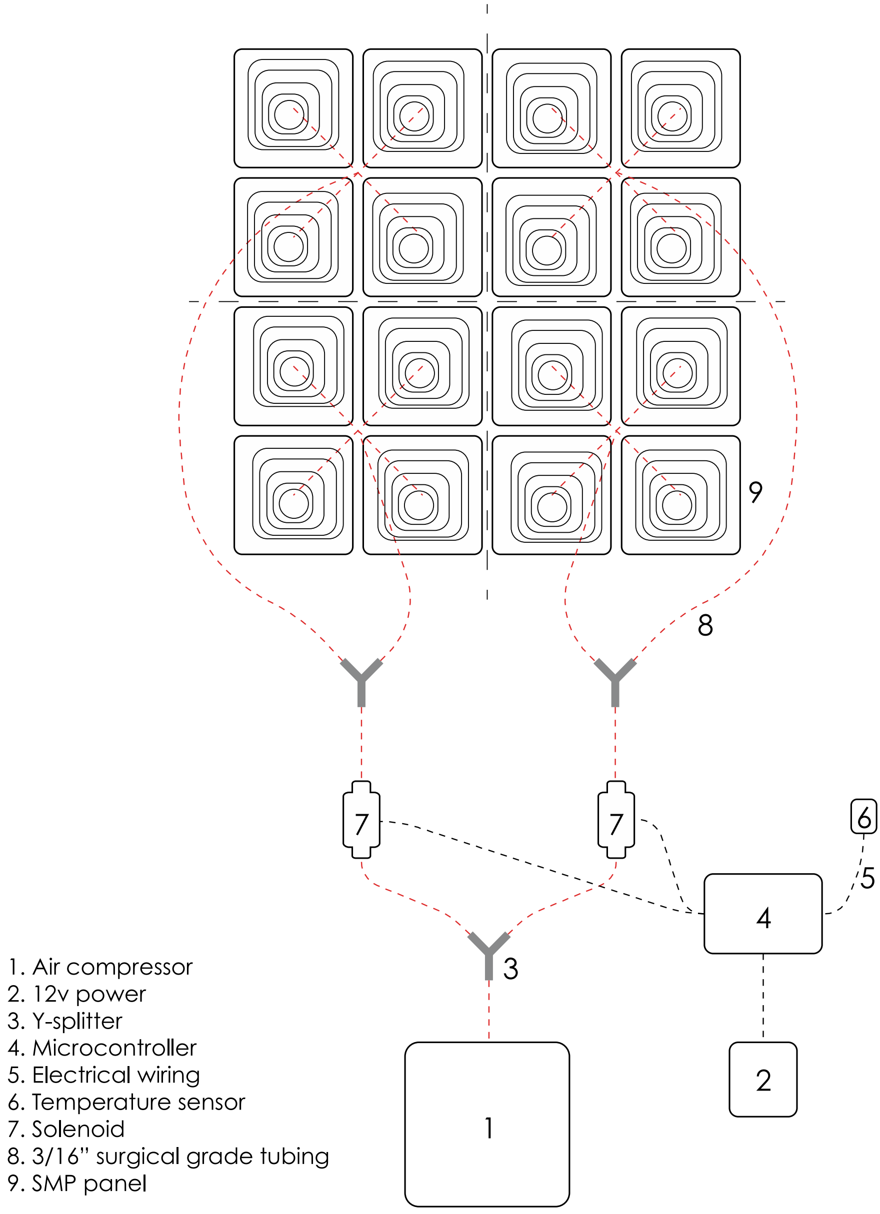

Fig. 12.8 Schematic of pneumatic inflation and control system. Schematic drawing of a 4 × 4 tile layout. Compressed air is distributed to the SMP tiles once their transition temperature is reached, causing the tile to deform. Upon cooling, the tile retains the deformed shape, and the air supply is no longer needed to retain the shape. Upon reheating to the transition temperature, the tile recovers to its' programmed shape

Ornamentation is often viewed as gratuitous, though it can contribute meaning to a building through its symbolism and impart delight, wonder, and sometimes reveal to us that we are part of a larger story. Programmable materials offer a step towards active and functionalized ornamentation that visually and thermally convey their response to local environmental changes. It seems valuable to consider the semiotics of emerging adaptive building technologies as the activated façade can become the literal performance of the building, calling into question the way in which we visually and thermally relate to architecture. The projects presented are a step toward the work of a confluence of artists, engineers, material scientists, and architects that no longer view architecture as a static backdrop which we live our lives against, but a dynamic and communicative condition that continually engages us with environmental flux.

To suggest that architecture alone can change the way one thinks or acts, is overreaching, but the potential for responsive design technology to inspire one to change their associations and relationships with the natural world is possible. Herbert Marcuse argues that "Art cannot change the world, but it can contribute to changing the consciousness … of the men and women who could change the world." (Marcuse, 1979) Taking a conceptual leap, we could apply Marcuse's thinking towards aesthetics and ecology, and propose that awareness of environmental fluctuations, through the filter of responsive architectural systems, may contribute to a shift in our attitude towards the energy we use and the world we inhabit.

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