BUILDING ENVELOPE INNOVATION

SMART FACADE FOR SHADING OF BUILDINGS

SUBMITTED BY

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Building Envelope Innovation: Smart Facade for Shading of Buildings

A Major Qualifying Project submitted to the faculty of
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in partial fulfillment of the requirements for the Degree of Bachelor of Science

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Abstract

With a focus on dynamic facades and overall building energy efficiency, this project resulted in a shading device that implements the use of a shape memory alloy, specifically Nitinol, to directly respond to solar heat. To evaluate the concept, a prototype was constructed and tested, forces were calculated, and energy modeling software was used to calculate the energy savings in comparison to an unshaded baseline. The result was an energy and user independent functioning shading device that effectively lowered annual energy consumption that is comparable to other types of fixed shading yet offers a new responsive effect on the architectural impact of a structure.

MQP Design and Professional Licensure Statement

Design Statement

This Major Qualifying Project focused on designing a responsive shading device that could be applied to standard buildings to reduce HVAC loads due to solar heat gain. Beginning with a broad concept of designing a futuristic, innovative, and responsive facade system, the team worked through many ideas to eventually settle on a shading design. Materials were researched, mechanisms tested, and architectural design considered. The long reaching goal of this design is to be adaptable to different facade systems in order to have a cultural and architectural impact wherever it is implemented. The design proposed was created and evaluated structurally and mechanically. The entire team worked collectively on the design process but divided the main responsibilities of the structural and mechanical sections.

Structural

Members of the team evaluated forces working within the shading device to optimize functionality. Loads on the entire building's facade due to the addition of this device were also determined. These calculations were made with primarily safety and public health in mind. A shading device that operates with a high percentage of functionality lowers potential glare that inhabitants are subjected to. Further, in a basic sense, ensuring that a building's structural system can withstand the added weight of this system keeps everyone safe.

These structural components were completed by Stephanie Jones and Katherine Johannes and reviewed by Sofia Reyes and Faye Gauthier.

Mechanical

Within the design process, the team compared the use of different materials to provide shading in both the working prototype and in an actual installation. A realistic building model in Design-Builder was created to calculate energy savings in comparison to standard fixed shading. Also, energy codes, fire protection codes, and HVAC standards were researched to implement into the design and the report. Further, members of the team created a window detail drawing to illustrate the integration of the design into a construction setting. These components helped the project achieve awareness of environmental, economic, and global considerations. The driving force for installation of a concept such as our design is to lower environmental impacts due to energy consumption and save money on energy costs. Further, it is vital to understand the climate that this shading device could be installed in and how globally it will be altered or remain the same.

These mechanical components were completed by Sofia Reyes and Faye Gauthier and reviewed by Stephanie Jones and Katherine Johannes.

Professional Licensure Statement

The steps toward a successful career in engineering begin with an education prior to joining the professional arena. Then when working in the field, there is much more to learn past the college curriculum. By working under more experienced engineers, early-career engineers are able to achieve the level of knowledge necessary to become a reliable professional. Engineering designs are what ensure our built environments are safe for human inhabitants, and as a society the expectation for this work is at the level of high quality of safety for the user and the general public. Further than the societal level, any client paying for an engineering service is expecting work in return that accomplishes its purpose. The uncertainty lies with who is trustworthy to hire for these services. What is the standard for experience and knowledge that makes an engineer independently trusted one? This is where professional licensure comes in.

The process to become a Professional Engineer (PE) is very straightforward and a very important part of an engineer's career and professional image. To do this, one must first complete a degree from an accredited engineering program. Then the engineer must pass the Fundamentals of Engineering exam and work for several to gain progressive engineering experience under a current licensed engineer. Finally, the aspiring PE must pass the Principle and Practice of Engineering exam (What is a PE?, n.d.). After earning the title of PE, one's skills must continue to develop in order to maintain the license. Depending on the state they are licensed in, different educational requirements are mandated. At this point, engineers have the opportunity to join professional organizations such as ASCE, AEI and AIA which allows them to network with others and contribute to the community as a whole. In turn, PE's can prepare and seal engineering drawings for construction (What is a

PE?, n.d.). Advancement within one's career as well as the engineering field overall is reliant upon professionals obtaining Professional Engineer status.

Acknowledgements

Our team would like to thank our advisors, Professor Albano, Professor Farzin-Moghadam, and Professor Van Dessel for providing insight and guidance throughout the design process. Additionally, we would like to thank Russell Lang for his help in building the prototype. Without their help, our team would have been unable to overcome the obstacles which arose throughout the course of this MQP, and each member of our team would like to express our most sincere gratitude for their continued support.

Executive Summary

Residential and Commercial buildings are some of the largest consumers of energy globally. As sustainability practices become mainstream and regulations become stricter, emphasis on developing methods to reduce the mechanical load on these buildings increases. Dynamic facades are rapidly developing as a way to combat solar heat gains which, in some climates, can be a large contributor to a building's cooling load. While most dynamic facades utilize computerized devices based on temperature sensors, the incorporation of smart materials such as Nitinol, offers the unique possibility of adaptability without requiring additional power.

The goal of this project was to develop an autonomous shading device utilizing Nitinol as a device actuator. Throughout design and analysis, the focus was placed on creating a responsive device that could be easily incorporated in a building in a natural and aesthetically pleasing fashion. Different models were developed under this concept, and through the use of weighted evaluation matrices, the most promising design was pursued, which consisted of a vertical mechanism assembled from a Nitinol coil and tension spring working together to expand and contract an accordion-folded shade. A material specific matrices concluded that 110lbs paper was most promising because of its creasability and opacity. Following this selection, an investigation was completed to establish the appropriate tensile forces generated by the spring to counteract the Nitinol coil under the relaxed condition. After developing a balance between the internal forces acting on the spring and Nitinol, an analysis was completed to ensure the proposed design could be added to an existing building with minimal impact on the structural system. Design

effectiveness was tested through the use of physical prototyping and computer-based energy modeling. Using a scaled version of the proposed design in combination with artificial heat and light sources to replicate the sun, the design was tested for response time, speed of motion, and shading effectiveness. Following these tests, it was concluded that within an hour of initiating activation the device was able to reduce light infiltration by almost two-thirds. Using the software Design-Builder to evaluate annual energy consumption, the proposed design has an estimated 3-5% energy consumption reduction in comparison to an unshaded baseline. This range depended on several variables: location, amount of window panes, and activation temperature of the design.

Following the analysis of the results as a whole, the proposed design was proven to be a functional concept for the integration of smart materials into building components as an energy saving initiative. Based on evolving materials and ideas, the proposed system offers many future opportunities for investigation of the active concepts and optimization of smart material mechanics.

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1. Introduction

In 2018, the energy utilized to provide cooling to residential and commercial buildings accounted for 9% of the United States' electricity consumption. While this percentage seems relatively low, commercial buildings alone consume around 163 billion kWh annually (U.S. Energy Information Administration, n.d). In many climates, solar heat gain is a large contributing factor to a building's mechanical cooling load. While solar heat gains are beneficial at lowering heating loads in the winter and lighting loads using daylighting, solar heat gains can greatly increase the temperature differential that needs to be overcome through cooling in the summer. Shading devices alone have been proven to reduce the solar heat gain by almost 80% under optimal conditions (Solar Shading Saves Energy, 2016). Fixed overhangs use existing knowledge of seasonal solar patterns to allow for beneficial solar radiation during heating dominated months and block solar radiation during cooling dominated months. These fixed overhangs operate passively, but do not provide the flexibility to account for the different angles of the sun throughout the day. As an alternative, automatic shades use external energy sources connected to an outdoor temperature sensor to operate a shading device based on what is optimal for the internal environment (Passive Solar Home Design, n.d.). These systems provide the adaptability that the evolving world desires, but counteracts much of its energy savings by relying on external power. This added complexity also increases the system's risk of failure.

This project aims to design a shading system that intrinsically responds to external stimuli to reduce the solar heat gain within a building, without user intervention or additional power sources. The extent of this project includes designing a responsive shading system and evaluating this system as an effective way to reduce energy usage in a building. We utilized both physical prototyping and computer-based modeling tools to optimize the interaction of the active mechanisms, to evaluate the impact of design implementation on an existing commercial office building, and to test the effectiveness of the system at reducing energy usage.

2. Background

Adaptive building facades provide a unique opportunity for innovation within the built environment. Such systems have begun to be developed internationally as a solution for environmental sustainability and intriguing architecture. While most dynamic facades utilize computerized devices based on temperature sensors, smart materials including thermo-responsive materials offer unique characteristics that makes them ideal for future advances.

2.1 Dynamic Facades: Adaptive Solar Shading

In a broad sense, a building facade must provide protection from the environment but allow for adequate connection between the outdoors and individuals (Aksamija, 2013). The envelope of the building is what separates the interior space from the exterior climate, acting as the building's skin. Additionally, the facade plays a large role in the energy consumption of the building as it can dramatically impact the heating, cooling, lighting, and ventilation of interior spaces. These four categories alone account for more than 50% of the building's energy use (Aksamija, 2013).

In Europe, building energy standards will be extremely stringent after 2020, with overall net energy requirements coming very close to zero (Hraska, 2019). Further, as architectural trends demand a higher window to wall ratio than ever before, facade systems are becoming more of a detriment than a benefit to the building's energy consumption. Despite these new challenges, advanced technology allows designers to consider dynamic facades as a solution instead of the traditional approach of a simpler static facade. A dynamic facade reacts based on external stimulus that would cause the need for a change in the building's interior systems or environment (Hraska, 2019).

Dynamic facades are the largest proponent of responsive building design because the building envelope separates the interior building space from the elements. The most significant characteristics of a dynamic facade are adaptive solar shading devices (Hraska, 2019). With an increasing need for more efficient buildings, dynamic facades are more relevant (Hraska, 2019).

Shading components within a dynamic facade provide an adaptive solution to combat the growth of both stricter efficiency standards and glazing trends in modern building design. Adaptive shading serves the purpose of reducing energy consumption and increasing visual comfort in an active way (Hraska, 2019). Other components considered in an adaptive shading facade are how the solar energy is regulated, smart materials, classification of movement, biomimicry, and more.

2.2 Impact of Shading in Interior Systems

Typically, shading devices require manual power or electricity in order to fully operate. For example, standard indoor blinds require a human to unlock or lock the shades in place. Electronic shading devices, including electronic blinds, allow a shading device to be completely responsive to the surrounding environment, thus providing many benefits for standard buildings. With an automatic shading device, users do not need to worry about glare, office heat gain, or adjusting the shades whenever the sun rotates.

With a responsive shading device comes an impact on the building's HVAC and artificial lighting loads (Bellia, Marino, Minichiello, & Pedace, 2014). There are benefits and drawbacks to automatically responsive shading devices. In terms of lighting, these systems can reduce glare for the inhabitants but will increase the need for artificial lighting and thus increase energy consumption (Bellia, Marino, Minichiello, & Pedace, 2014). In terms of HVAC loads, a responsive shading device will block solar radiation from heating the interior space when it is activated. This will reduce the cooling load, but if used throughout the year, it will increase the heating load in colder winter months (Bellia, Marino, Minichiello, & Pedace, 2014). Finding the balance between these lighting and heat gain factors is what makes a successful design.

2.3 Current Technologies and Standards

Some examples of adaptive shading being implemented around the world are the Arab World Institute built in 1987 by and ThyssenKrupp Quarter (Q1) built in 2010. The Arab World Institute in Paris designed by Jean Nouvel, Architecture-Studio, Pierre Soria and Gilbert Lezenes is covered in small shutter-like devices that are powered by individual motors (Figure 1). This feature has experienced many malfunctions since its installation that rendered the design much more difficult to operate successfully (Hraska, 2019). JSWD Architekten and Chaix & Morel et Assoociés, the designers of Q1 in Germany implemented louvers that move according to the sun's position. Due to advances in technology, this design has functioned better than the Arab World Institute in the long term. Although this design accomplishes regulation of daylight to meet applicable standards, there is a limited response based on the occupant's individual needs (Hraska, 2019).

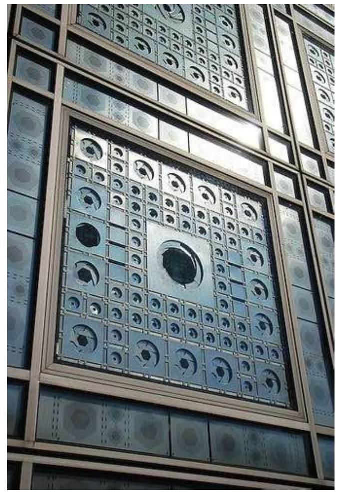


Figure 1- *Dynamic Facade from Arab World Institute*

In the previous century, it was not a priority to incorporate architectural elements designed to increase energy efficiency. As technology became more accessible to engineers and architects, it became more feasible for architects to ignore applicable climate parameters in their design, and rely solely on installing sizable HVAC systems to make the indoor space livable (Perino & Serra, 2015). This allowed them to design any type of modern facade without energy efficiency in mind. Today, the efficiency of buildings is more highly valued.

To achieve efficiency through design and construction there are several codes and standards. For example, aspects of HVAC are outlined by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). Additionally, energy consumption baselines are defined by the *International Energy Conservation Code* (IECC). Many efficiency requirements of different portions of a building are reliant on the relevant climate zone. The IECC outlines the parameters to meet Total Building Performance based compliance. This method incorporates the overall heating systems, cooling systems, service water heating, fan systems, lighting power, receptacle loads and process loads.

Performance based regulations consider the end results of the design, and does not govern the means to get there. The IECC Total Building Performance section is based off of this. Alternatively, there are regulations that govern the means that achieve a final performance. This is called prescriptive regulation, which is commonly found in ASHRAE standards.

Finding the balance among these factors is not easy but as technology has advanced, several parametric tools have been developed to help designers achieve the standards set by ASHRAE and IECC. Relevant modeling and analysis design tools include DesignBuilder, a building software that analyzes a digital architectural model to help the user analyze expected energy consumption. This program creates high-quality simulations with the option of compliance with ASHRAE 90.1 (2007 or 2010) building requirements. The user inputs basic information of the project (e.g. building type, location and components such as walls, windows and roofs), and the software completes a compliant computational analysis of building energy consumption (Zhang, 2014). Design tools like DesignBuilder are key to the development and adoption of new building technologies.

2.4 Shape Memory Alloys (SMA)

Often the effectiveness of a building component is measured by its long-term performance and its ability to cope with environmental changes. In the case of this project, we are looking to create an effective, long-lasting device that counteracts the impacts of solar gains on a system. One strategy to accomplish this is implementing a new material that is responsive to the climate. Consequently, a relatively new material used in this project was a thermo-responsive material that falls under the category of stimulus-responsive materials (SRMs), specifically shape memory materials (SMMs). SMMs are materials that have been trained to return a desired shape when exposed to an external stimulus, also known as the shape memory effect. (Sun, 2012)

There are several types of SMMs that have been developed so far, including polymers, alloys, and hybrids. Shape Memory Alloys (SMAs) are currently the most well studied SMM as they have been previously utilized as actuators in many different commercial applications. (Sun, 2012). The extensive research highlighting the structural potential and high cyclability of SMAs produces a high desirability in emerging innovative technologies.

Shape Memory Alloys (SMAs) are typically fabricated in the form of wires that can be distorted to any condition, then when exposed to the external stimulus it returns to its trained condition. These wires have been utilized as sensors and actuators in conventional electronics because they save space, weight, and power supply compared to typical assemblies as well as creating a force during temperature changes (Habu, 2011). SMA wires are typically made up of metallic materials with multiple crystalline structures, determined by internal stresses.

The three most popular SMA's are Copper-Zinc-Aluminum (CuZnAl), Copper-Aluminum (CuAl), and Nickel-Titanium (NiTi, also known as Nitinol). The CuZnAl SMA was one of the first copper based SMAs. Its transition temperature between -100C and 100C is very useful, however, its memory capability is one of the weakest. Low memory capabilities can reduce the functionality and efficiency because it would require more maintenance and reduce the life span. The CuAl SMA is another copper based SMA. Although this specific SMA contains relatively inexpensive metals, the transition temperature is too high for most applications. Lastly, the Nitinol SMA is capable of tolerating large amounts of memory strain; it is also extremely stable and corrosion resistant. This specific SMA is rather difficult to manufacture due to the reactivity of Titanium, yet it has the widest application in many fields including Biomedical Engineering and Mechanical Engineering (Barnes, 2019).

2.5 Nitinol

Nitinol is a shape memory alloy that has increased in popularity in the last couple of decades because of its ability to carry much higher strain loads than conventional metals. This is due to the fact that nitinol wires exhibit constant unloading stresses over large strains (Duerig, 1999). Nitinol is considered to be superelastic as it has an elastic response to applied stress. Consequently, the force applied by superelastic materials like Nitinol is determined by temperature, not strain as in common materials, allowing a stress-induced (heating-cooling) transformation.

Superelasticity in Nitinol is caused by a phase transformation between two different crystalline structures, austenitic and martensitic phases. The change between phases impacts its material characteristics and properties. This change occurs at a certain temperature, called the transition temperature. Nitinol changes from its bendable state to its original rigid state. When a Nitinol wire is below its transition temperature, the crystalline structure becomes an asymmetric cubic structure. This state is called martensite, allowing for it to be easily deformed. When heated above the transition temperature, the crystal structure becomes symmetric and allows the wire to return to its memorable state. This state is known as its austenite phase, rigidly returning to its "trained" shape. This described Nitinol transformation process is outlined in Figure 2.

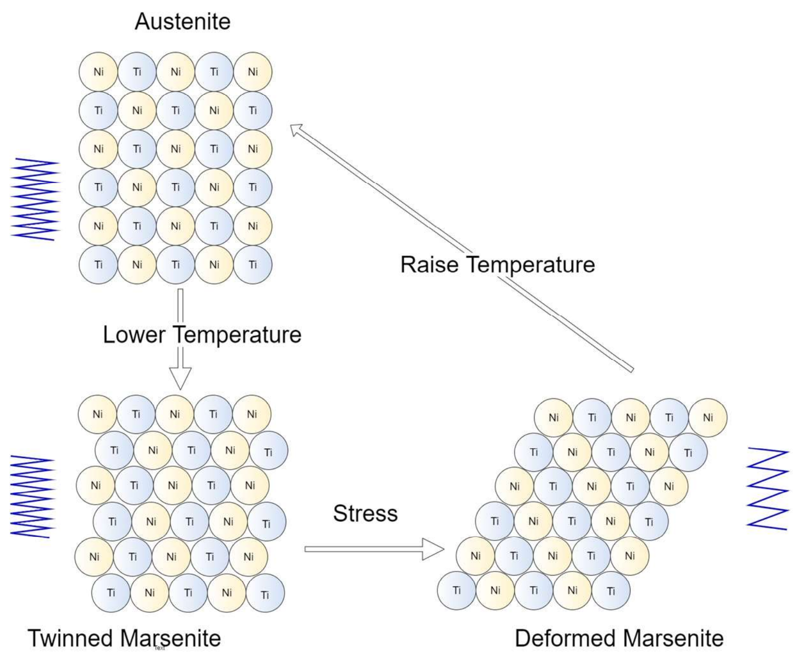


***Figure 2**- Nitinol Crystalline Structure: Superelasticity Phase Transformation*

If a new memorable design or shape is desired, the Nitinol wire must be heated up to a temperature of 500 degrees Celsius. When in that state, the Nitinol can be manipulated into any new memorable shape.

3. Design & Analysis

The goal of this project was to design a concept for the facade that has the ability to react to changes in solar radiation in order to create a comfortable and more energy-efficient indoor environment. In addition to designing a dynamic and adaptive solution, our vision was to design a facade system that maintains a welcoming sensation to the human eye. We worked to accomplish this with a concept composed of an irregular shaped pattern (Figure 3). This pattern would incorporate an aperture motion within each unit to provide shading. The components of the mechanism had to be represented in a way that those passing by would not be distracted. However, the entire design does not have to be "hidden" as leaving a portion of the mechanism viewable in a way that allows people to be intrigued by the overall design. The pattern was designed to be incorporated within the framework of an existing curtain-wall facade.

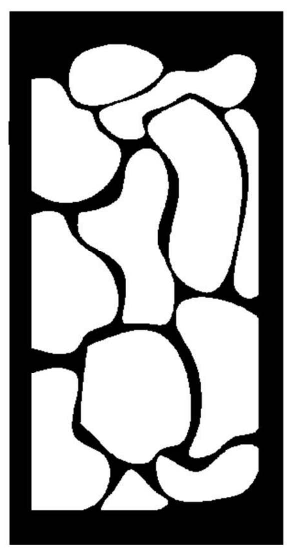


Figure 3- *Irregular Pattern*

One of our design priorities, besides the interaction with the outside, was the mobility. We wanted a regulated response that would build up over time as opposed to a sudden action. This was achieved with the incorporation of SMA wire, specifically Nitinol. To protect the mechanism from the disruption of the outside interference, we integrated the design within the cavity of a layered glazing system. The cavity in between the glazing creates an "intermediate" environment where the SMA wire can expand and contract in relation to the temperature. This enclosed environment will also protect the product, producing a longer lifespan and lower maintenance costs.

The main focus of this project was taking this simple and idealized vision into a fully functional design. We worked on the following objectives to achieve this:

1. Investigating the use of Nitinol as a Thermo Responsive and adaptive material
2. Creating a shading device that utilizes Nitinol
3. Testing and evaluating the functionality and potential energy savings of the shading device
4. Investigating options for optimization of the setup of the shading device

The following sections will address our methodology in response to the above four objectives.

3.1. Investigating the Use of Nitinol as a Thermo Responsive and Adaptive Material

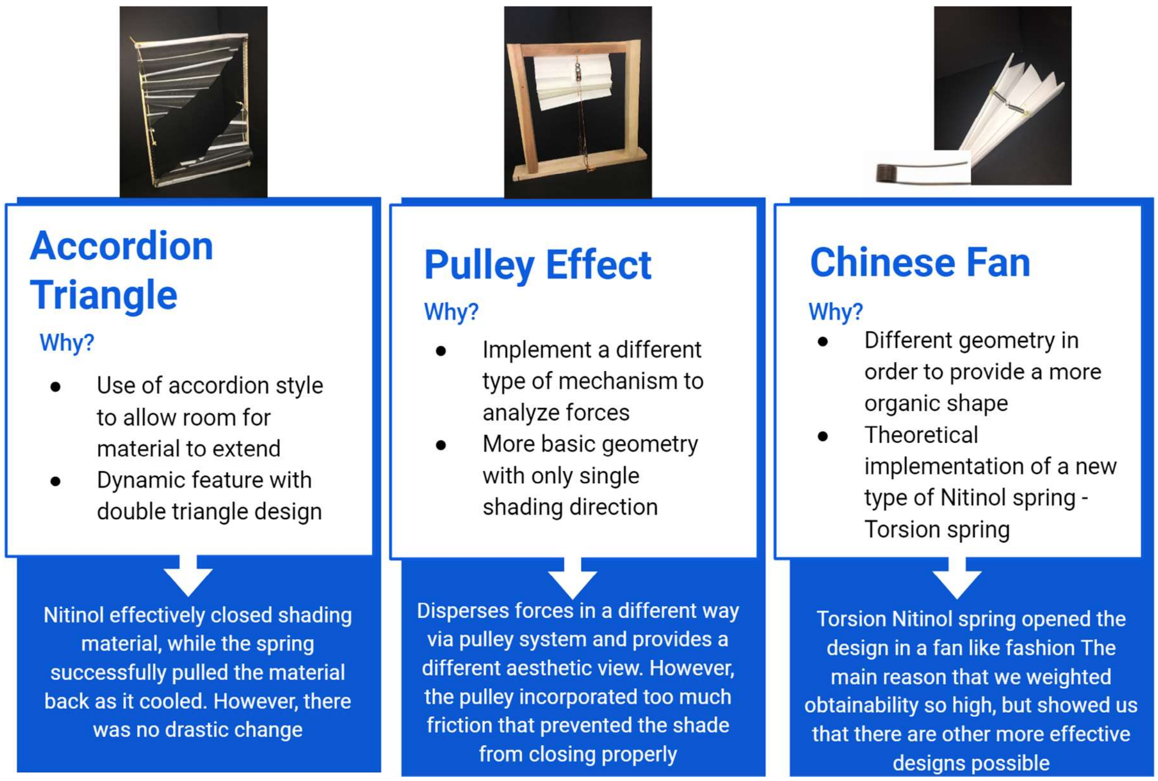
Our first design integrated the Nitinol in the middle of a wooden circular frame connected by elastic strings (Figure 4). As the wire was heated up it "closed" to create the aperture movement. However, the elastic material was not stiff enough to pull the Nitinol back out to a relaxed coil. The Nitinol did not return to its original shape, thus creating a cyclability concern with this design. To solve this issue, we looked into the use of two-way SMA wire; however, this product was not within the financial scope of this project.

Subsequently, we looked into other solutions that would incorporate springs or weights to create enough force to pull the coil back to its original shape during cooling. Springs provided a safer and more aesthetically pleasing result.

Figure 4 - *First design: Wood frame with SMA wire*

We tested the relation between different springs and Nitinol coils. When the Nitinol was heated it contracted and stretched the spring, and when cooled the tense spring was successful at pulling the Nitinol out of its trained shape. Following our success, we created several models, shown in Table 1, that incorporated this movement. Each design helped us understand this interaction of spring and Nitinol in different scenarios.

Table 1 *- Models Implementing Spring to Counteract Nitinol*



3.2 Creating a device that utilizes the Nitinol

After developing a few different designs using a Nitinol and spring mechanism, we needed to establish a way to effectively grade and evaluate our designs to determine the option that was the best for our specific project and application. We developed three different matrices to analyze and evaluate the material, the mechanism, and the overall design of the project. These decision tables contained a variety of characteristics or categories for assessing the components. In each category a component could receive a maximum score of 4 and a minimum score of 1. The grade received was based on numeric values that we could acquire, or written descriptions of what each grade entails (Appendix A). These categories were also assigned a weighting based on informed estimation of the component's importance to the functionality of the design. The sum of the received grades multiplied by the category weighting, gave us a systematic way to rank and ultimately select a design.

The first matrix completed was a shading material selection. We compared six different materials under seven different categories, shown in Table 2. The main category that had the most significant impact on material selection was creasing ability. This was deemed our most important category because in order to return to the "open state" the design requires force created by the accordion action caused by creasing, and creasing allowed for the clean opening action that we wanted. The second highest weighted category was the specific strength to ensure that the material would not rip and reduce maintenance in addition to the solar deterioration coefficient. Lastly, flammability and thermal conductivity address some of the performance factors of the device based on the material.

Table 2 - *Comparison of Shading Materials Matrix*

Material	Specific Strength	Crease	Thermal Conductivit y	Opaci ty	Cost per sqft	Flamma-bility	Solar deterioratio n	Total	Rank
Weight	20	35	10	13	2	15	5	100	
110lb paper	1	4	4	3	3	2	2	**71.25**	**1**
80lb paper	1	4	4	3	2	2	2	70.75	2
Charcoal Fiberglass Insect Screen	2	1	4	2	3	3	3	51.75	5
BetterVue Screen	2	1	4	4	3	3	3	58.25	4
Fiberglass Sheet	3	1	4	3	2	3	2	58.25	4
Ceramic Fiber Fireproof paper	2	4	3	2	1	2	2	69.5	3

A similar process was repeated to analyze the active mechanism that makes the system thermally responsive. This process evaluated a Nitinol coil design, a Nitinol and pulley combination, and Nitinol torsion spring. The evaluation of these mechanisms was based on the categories weight, potential for failure, obtainability, range of motion, integration, cost and scalability, as shown in Table 3. Obtainability was the highest weighted category because without adequate access to the working mechanisms, we are unable to test the function of the design and calculate accurate operating values. The next highest weighting is the potential for failure. While there is a proven concept for a Nitinol/Spring Shading system, potential for failure addresses the long term cyclability of the system and successful operation.

Table 3 - *Mechanism Comparison Matrix*

MECHANISM	Weight	Potential for Failure	Obtainable	Motion	Integration	Cost	Total	Rank
Weight	10	15	40	20	5	5	100	
Coiled Spring	4	3	4	2	3	4	**82.5**	**1**
Torsion Spring	4	3	2	3	4	2	66.25	3
Pulley System	2	2	4	2	4	3	73.75	2

Table 4 shows our final analysis that we completed to assess the combination of the Mechanism, Material, and other complete design components. This final assessment was our greatest opportunity to systematically and completely gauge the best design choice for further investigation. Based on the combination of these three comparison tables it was determined that the best combination of variable was the use of 110lbs paper and a Nitinol coil in a triangle accordion design. Consequently, we combined the use of physical prototyping and parametric design tools to further develop our design.

Table 4 - *Design Comparison Matrix*

Category	Weight	Triangle Horizontal Accordion	Chinese Fan	Pulley
Material (table 2)	20	71.25	71.25	71.25
Mechanism (table 3)	50	82.5	66.25	73.75
Maintenance due to Failure	10	3	2	3
Scale	10	4	2	3
Innovation	10	2	3	2
Total	100	**78.0**	64.9	71.1

3.3 Testing the Functionality of the Device

Design functionality was a priority throughout the entirety of the project. To optimize the design, we tested our system in two different levels, component performance and overall performance. The component performance refers to the shading device itself and tests the functionality of its internal elements. These internal elements include proper spring size selection, efficiency of the shading material, and the axial deformation of the springs acting on the joints of the frame. The overall performance testing refers to the overall weight added to the building based on when the shading device is applied to the facade and the energy performance results obtained from DesignBuilder, a building energy modeling software tool.

3.3.1 Component Performance

A scaled-down prototype was designed and built to give an estimation of the proposed design's functionality. We housed our prototype in an acrylic box, with a wood base to take the place of a typical layered glazing system (Figure 5). This setup allowed us to have easy adaptation throughout the testing and development process as well as create a transportable and cost-efficient model. Taking the place of the sun as activating force, we used a 250W heating lamp positioned about 0.5 inches above the top of the wooden base. A wooden frame was built and bolted to the wooden base to provide support for the acting mechanism of the prototype.

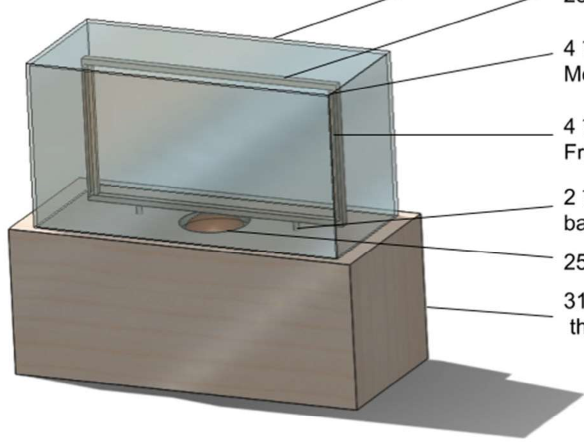
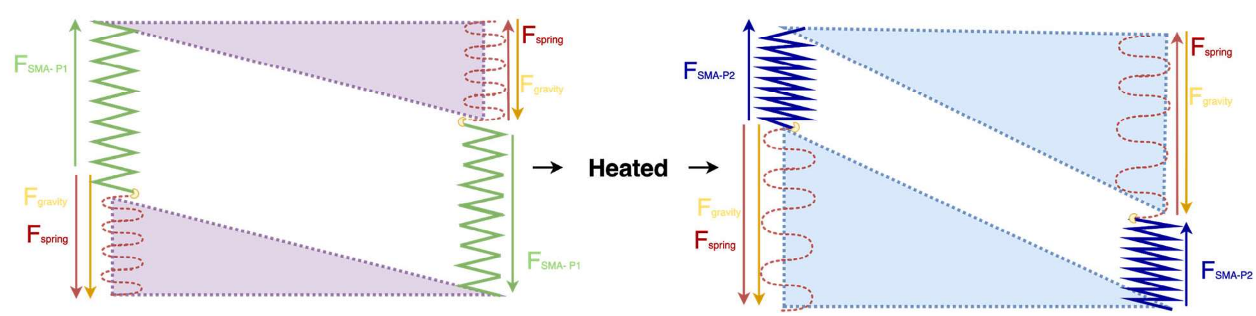


Figure 5 *- Schematic of an Acrylic Box*

3.3.1.1 Internal Force Balance

The acting mechanism was created using a spring, Nitinol coil, and folded paper that was put in place to balance the internal forces that cause the reactive movement of the shading device (Figure 6). We conducted internal force analyses to determine the correct ratio of the components within the system to ensure and optimize operation. These analyses focused on the spring force interaction between a Nitinol coil and a counteracting spring force created by a linear spring acting in combination with an accordion-folded paper. The utilization of Hooke's Law to determine the elastic capability of materials provided idealized characteristics for a spring based on the properties of the Nitinol and the folded paper. These forces as well as gravity act on the proposed design as balances under both relaxed and active conditions (Figure 6).

***Figure 6**- Internal Force Calculation*



A spring that functions as desired in this system had to have an elastic force that was lower than that created by the Nitinol when it was activated but higher than the same Nitinol coil when it was in its relaxed condition. To determine the balanced condition, we used Hooke's Law and a displacement compatibility condition (3.1) to derive an expression for the displacement of the components(ΔL)and the respective forces exerted by the components (F) and their spring constants (K).

$$\Delta L - (F/Knitinol) = (F/Kspring) + (F/Kpaper) \qquad \textbf{(3.1)}$$

A set value for the change in length $\Delta L$was determined by taking the prototype frame height (12”) and subtracting the initial length of both the Nitinol coil (1”) and an estimated relaxed length of the spring (1.5”). The resulting 9.5” was used as the ΔL value, assuming that the spring and Nitinol would have 100% efficiency. This value was also used to determine the forces and spring constant properties of Nitinol and the paper shade. Both of these components were attached to an Instron tensile tester and had their forces mapped intermittently every 1 cm from 0- 9.5”. The slope of the trendline of the component’s Displacement v. Force graph defined the component’s unique stiffness value K. Using the calculations as a guide we selected 3 different springs based on the current market solutions that most closely resembled our results.

3.3.1.2 Prototype Testing

Using this prototype, we tested the activation speed, the speed of movement, and the shading performance of the proposed design. These values were taken concurrently, and recorded at three different times to establish consistency among the tests. The prototype was placed in a dark room with black foam boards placed around the top, back and sides of the box to block external light from affecting the results. To quantify results, a ruler was placed alongside one side of the frame, and a GoPro Camera was placed outside of the prototype to record a time-lapse video of the movement over time. This time-lapse could be further analyzed to see how long it takes for the mechanism to become activated and, once activated, the rate of movement over time. The general prototype testing set-up is shown in Figure 7. In total, the design was allowed to be activated for a full hour to ensure it reached its full activation and then it was allowed to relax for another hour.

To determine the shading performance of the design we used a light meter to determine the footcandles at various locations and settings. A baseline was found by placing the light meter in the center of the front side of the acrylic box before turning on the lamp to activate the design. We used an artificial lamp to replicate the sun as a light source. Under the same conditions, the light meter was also placed about 12 inches behind the prototype while still enclosed by the black foam box. Both of these measurements were rerecorded following an activation cycle, where the device was at its most closed.

Figure 7 *- Prototype of the Proposed Design*

3.3.2 Forces Acting on the Building and Window Frames

To calculate the force on the window frame, the average weight of a triple-glazed facade for 12’x6’ area is calculated to be about 200kg (Glass, 2019). It is assumed that if the additional weight added by the proposed design is less than 20% of the window assembly the additional weight is considered negligible. This percentage is allowed as a 20% margin of uncertainty is applied to all dead loads within a building as a safety measure. If the additional weight is over this percentage additional steps will be required to add additional structural support to the beam and column system of the building.

To minimize unexpected lateral loads, torsion and bending with the elements in addition to promoting the visual aesthetics, the decision was made to incorporate the active mechanism into the cavities of an existing mullion system. Using a Shuco AWS 120 CC.SI window as a baseline model for applications, we were able to restrict motion of the device to only the vertical direction (Appendix F). Small 20-gauge metal posts were used as guides to connect and secure the shading material that was in between window panes with mechanism that was shielded by the mullion.

Last, the deformation of the support system due to axial loading was calculated. A spreadsheet was created (Appendix B) to solve for the axial deformation caused by the activation and relaxation of the shading mechanism (3.2). This deformation (X) is calculated using equation **3.2**(Suvo 2019). Figure 8 demonstrates the interactions among all of the variables used to solve for the axial deformation.

$$X = (8WC3n)/GD \quad (3.2)$$

W=Force exerted

D_s= *Diameter of the spring coil*

d_s=*Diameter of the spring wire*

D_N= *Diameter of the Nitinol coil*

d_N=*Diameter of the Nitinol wire*

C= D_s/d_s *and* D_N/d_N*[in]*

n= # of active coils

G= Modulus of Rigidity $(G = E/2(1+v)[\text{GPA}])$

E= Modulus of Elasticity

v= Poisson's Ratio

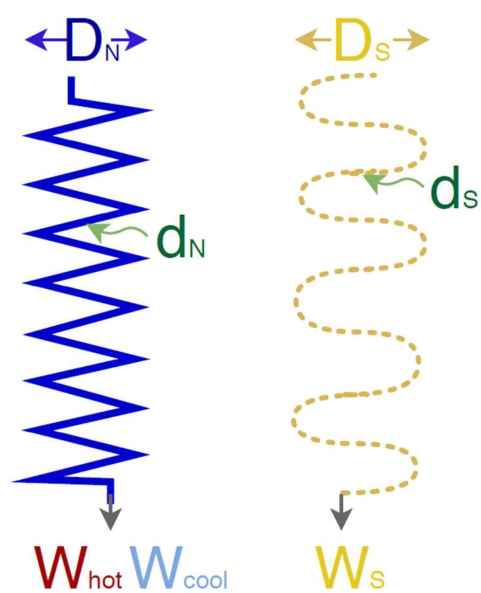


Figure 8- *Variables for Calculating Axial Load of the Nitinol (left) and the Spring (right)*

3.3.3 Energy Simulations

To investigate the energy performance of our shading system we used DesignBuilder to create energy simulations. Computer simulations such as DesignBuilder provide a quick and reliable alternative for predictions in building modeling. Simulation supports the consideration of several alterations in design parameters, but it requires proper definition of data, including constant and altered variables.

3.3.3.1 Constant Variables

Consequently, after defining constants and variables, shown in Table 5, we were able to run several simulations. These simulations were used as a tool to explicitly calculate the effects our design is in comparison to baseline cases.

Table 5- *Constants and Variables input to DesignBuilder*

<table>
<tr><th>Lighting</th><th>Shading Device</th><th>Openings</th><th>HVAC</th><th>Occupancy</th></tr>
<tr><td>Power density=.975482 W/ft^2</td><td>1m fixed overhang</td><td>40% Window to Wall

Window Height 4.92 ft</td><td rowspan="2">VAV air cooled chiller reheat</td><td>Density of 200 ft^2/person</td></tr>
<tr><td>Radiant fraction= .72

Visible fraction= .18</td><td>Midpane blind with medium reflectivity slats
Controlled by outdoor temperature:

Activation temperature of 80 degrees F or 90 degrees F.</td><td>Triple
6mm pane
Air gap=1”
6mm pane
6mm air
6mm air
or
Double
6mm pane
6mm air
6mm air</td><td>Metabolic Activity= Light Manual Work</td></tr>
<tr><td colspan="2">Schedule= ASHRAE 90.1 Availability -Office</td><td colspan="3">Schedule= ASHRAE 90.1 Occupancy -Office</td></tr>
</table>

In every case, an ASHRAE compliant 10 story office building (100ft by 100ft) was modeled with 15 ft floor-to-ceiling height (Figure 9).

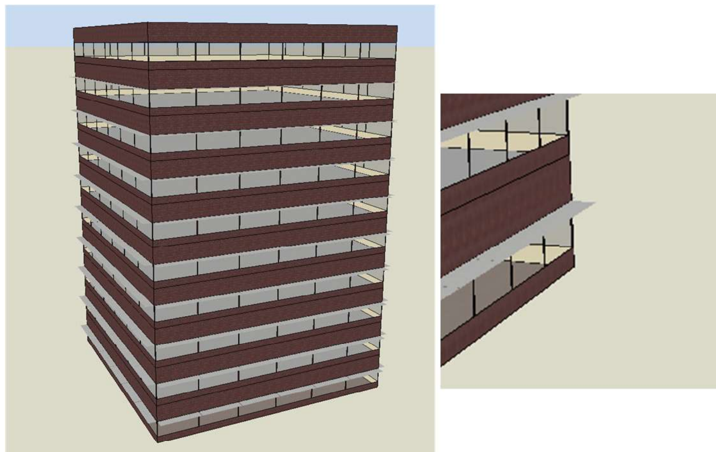


Figure 9- *DesignBuilder Model with Overhangs*

3.3.3.2 Altered Variables

It was manipulated to calculate without any shading, with static overhangs, and with our mid-pane design scenario. Further, simulations with overhangs and our design located on different sides of the building were conducted to accommodate the different angles at which the sun hits the building: first on each side of the building, then solely on the west, south, and east sides. This breakdown can be visualized in Table 6.

To determine the cases, three variables were altered in order to gain a wide sense of the design's abilities. These three variables were geographic location, number of glass panes in the windows, and outdoor activation temperature of our design. The simulations were made in geographical and climate zone (as defined by ASHRAE standards) of three different locations: Phoenix, AZ is zone 2, a dry cooling dominated climate; Nashville, TN is a zone 4, a humid and mixed climate; and Worcester, MA is zone 5, a humid heating dominated climate. As shown in Table 5, two additional variables we changed were outdoor activation temperature and the amount of panes in the window. Table 6 summarizes how the simulation outputs would be organized in order to be compared.

Table 6- *DesignBuilder Simulation Outputs*

	Phoenix, Arizona	**Nashville, Tennessee**	**Worcester, Massachusetts**
Double Pane	No Shading	No Shading	No Shading
	Overhangs	Overhangs	Overhangs
	Design (90deg F)	Design (90deg F)	Design (90deg F)
	Design (80deg F)	Design (80deg F)	Design (80deg F)
Triple Pane	No Shading	No Shading	No Shading
	Overhangs	Overhangs	Overhangs
	Design (90deg F)	Design (90deg F)	Design (90deg F)
	Design (80deg F)	Design (80deg F)	Design (80deg F)

Model Validity

Further, simulations were conducted without any components that rely on energy except the HVAC system to validate the model's outputs. Occupants and lighting were removed to detect changes that were based solely on the shading changes. The results were greater than but proportionate to those that accurately accounted for the typical loads an ASHRAE modeled baseline would have.

4.Results

The use of physical prototyping and simulations provide a thorough investigation of the strengths, weaknesses, and potential applications of the proposed design. These comprehensive tests give an understanding of the operation of the design and the potential implications of its application to a building.

4.1 Prototype

Scaled physical modelling was essential for investigating the interaction of acting components within the system, both for optimization purposes and functionality. Tests such as internal spring performance and shading efficiency was completed on the prototype in multiple trials to provide an accurate representation of the operation of the proposed design. (Figure 10) Each aspect of the prototype testing informed further tests and operation throughout the duration of the project.

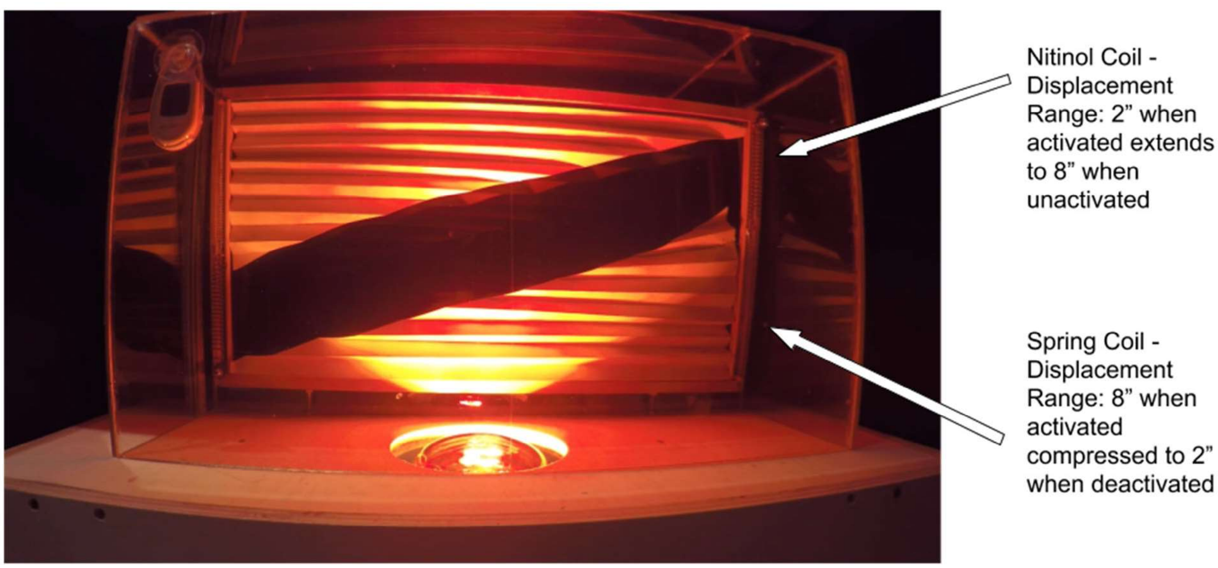


Figure 10- *Prototype Components*

4.1.1 Internal Spring Performance

In order to deform the Nitinol in its Marsenite stage, a spring was used to counteract the recoiling done during the Nitinol's transition to the Austenite phase. The counteracting spring constant was calculated with a change in length of 7.5". The calculated spring constant was dramatically lower than most standard springs. The spring constant, when the Nitinol was cool, was calculated to be 0.19 N/cm, and when the Nitinol was hot, the spring constant was calculated to be 0.128 N/cm. With that being said, a variety of springs were purchased from the *The Spring Store* with various spring constants between the values mentioned above. Once the springs arrived, each was tested, and the results were recorded to determine which spring performed best when connected to the Nitinol. Once this physical testing was complete, it was concluded that the spring with a model number of *pe020-312-66101-sst-1750-mh-n-in* was the best fit for our shading component.

4.1.2 Prototype Results

After testing the reaction time and speed of motion during the activation and relaxation cycles of the prototype, it was determined that after initiating activation of the heat lamp, it took the Nitinol about 4 minutes and 25 seconds before it moved 0.5 inches. This was determined as the activation point. Following the activation time, it took the design approximately 2 hours before it reached its maximum displacement. Throughout the trials the maximum displacement achieved by the prototype was 6 ⅜". With this achievable displacement, it is concluded that the spring used, provided our prototype with a 61% closing factor.

We used a lightmeter at two different locations, shown in Figure 11, to determine the quantity of light that is able to pass through the prototype. Furthermore, we were able to investigate the change in light infiltration under the different operating conditions of the design. Under the relaxed "open" condition of the shading device, 27% of the light was transmitted from front to back of the Acrylic enclosure. Following an activation cycle, when the shading component achieved its maximum closure, the same test was repeated resulting in a 9% light transmission from front to back (Table 7). This is a 63.5% decrease from the "open" state of the device.

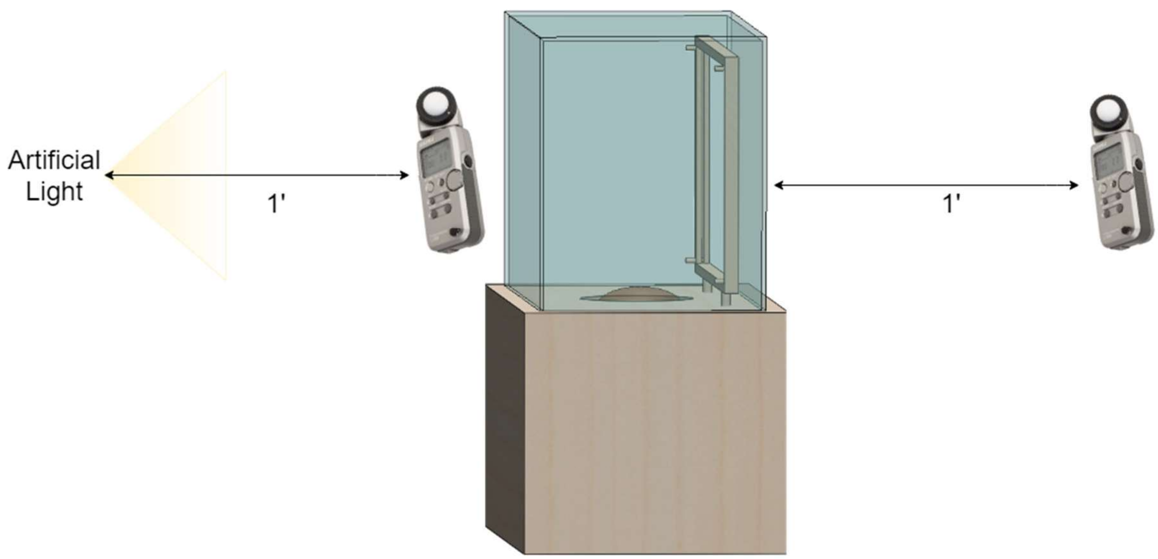


Figure 11- *Lightmeter Placement to Measure Light Transmitted*

Table 7- *Shading Efficiency*

	Pre-activation		Post Activation	
	Front*	Back*	Front*	Back*
Trial 1	35.6	9	36.5	3
Trial 2	32	9	37.2	4.2
Trial 3	29.1	8.2	36.7	3.7
Average	32.23	8.73	36.80	3.63
Shading Efficiency	0.271		0.099	
	27.1%		9.9%	

*Units: 1999-2000 Lux

Table 8 below represents the displacement of the shading device over time throughout the course of an activation and deactivation cycle. As shown, it took an hour and fifty-two minutes for the shading device to close to its maximum. Additionally, when the heat was deactivated it took the device an hour and six minutes for the paper to return to its relaxed state.

Table 8- *Reaction Time of the Proposed Design*

Displacement (Inches)	Reaction Time (When heat activated) (Hrs:Min:Sec)	Reaction Time (When heat is deactivated) (Hrs:Min:Sec)
1	0:04:31	0:06:15
2	0:14:50	0:16:47
3	0:36:22	0:27:33
4	0:57:32	0:39:04
5	1:21:16	0:51:21
6	1:52:04	1:06:53

4.2 Building Forces

For calculations it was assumed that this design would be implemented into a 12'x6' mullion system. Market available lengths of Nitinol coils and springs do not currently match what is required to scale the proposed design, modelled at 1'x2', to 12'x6'. For this reason, it is planned to stack 12 1'x6' models vertically in the existing framework (Figure 12). Furthermore, this stacked configuration into the mullion system had a combined weight of about 12.7 lbs (Appendix C). This additional weight is only about 6.34% of the average weight of a triple-glazed window system. This percentage is well below the standard margin of uncertainty. The typical margin of uncertainty when it comes to load and resistance factor design (LRFD) is 20% (Table 8).

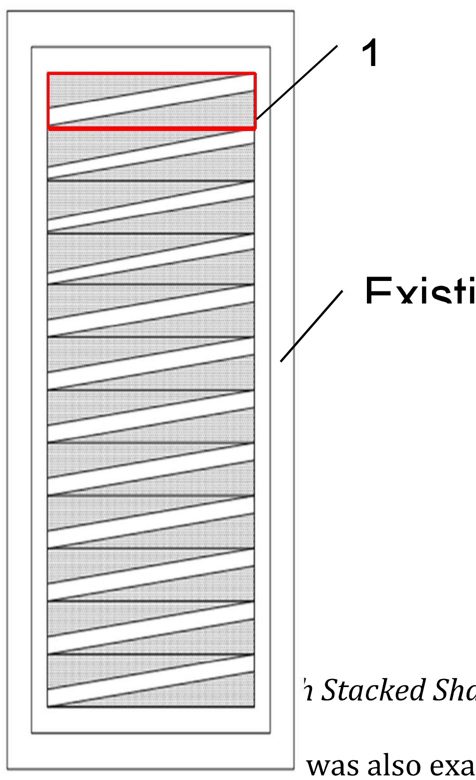


Figure 12- *Exis ... n Stacked Shading Units*

The deformation due to axi ... was also examined to determine the forces acting on the joints that support the shading device. The total axial deformation is the sum of the deformation caused by the force of the spring in addition to the deformation caused by the Nitinol. The joints will experience different deformations under the activated and relaxed states due to the changing forces acting on the joints. Using equation 3.2, it was determined that with the existing properties of the system the joints will experience a 0.35 mm deformation during the relaxed phase and a 0.34 mm deformation during the activated phase (Figure 13). These deformations are within normal limits and will not cause problems to the operation of the window or shading device (Table 9).

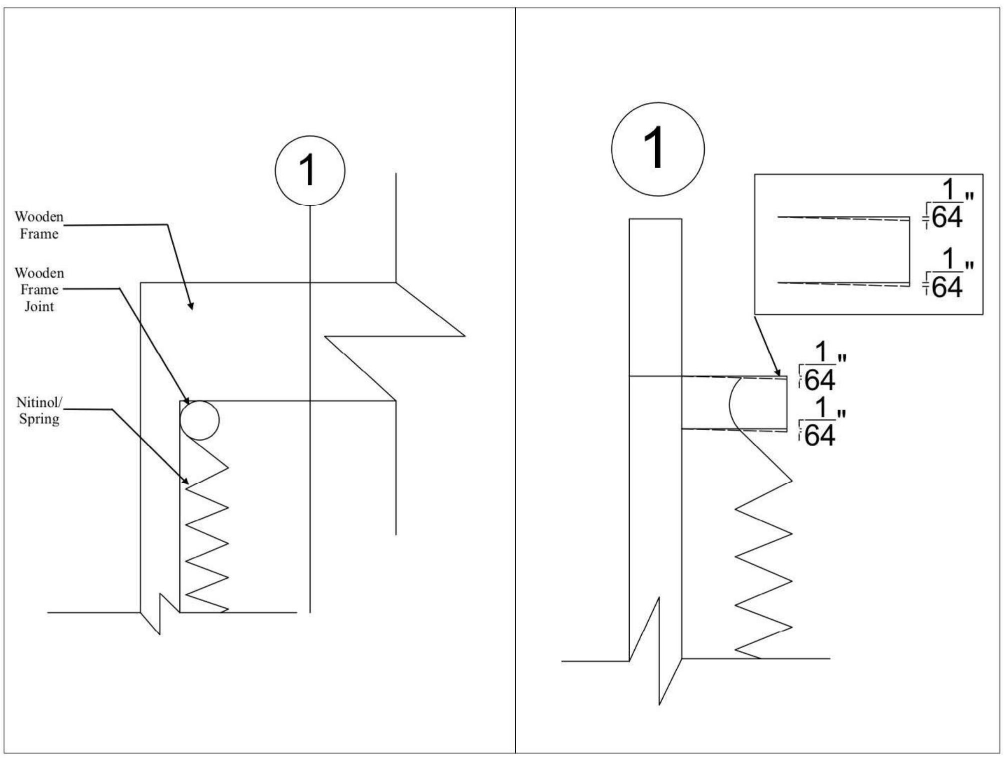


Figure 13- *Axial Deformation on Frame Joints Caused by the Forces of the Springs*

Table 9- *Forces Analysis Justification*

Maximum Limit	Reference	Prototype Limit
20%	(LRFD) 1.2*Dead Load + 1.6*Live Load	6.34%
0.0625" (1/16")	(AISC) Bolt Hole = Bolt size + 1/16"	0.014"

4.3 Energy Simulations

We created several cases in DesignBuilder to inform the further development of our design. The different cases had variables such as geographic location, number of glass panes in the windows, and outdoor activation temperature of our design to investigate functionality under different scenarios. (Figure 14) The full breakdown of all result cases can be found in Appendix D.

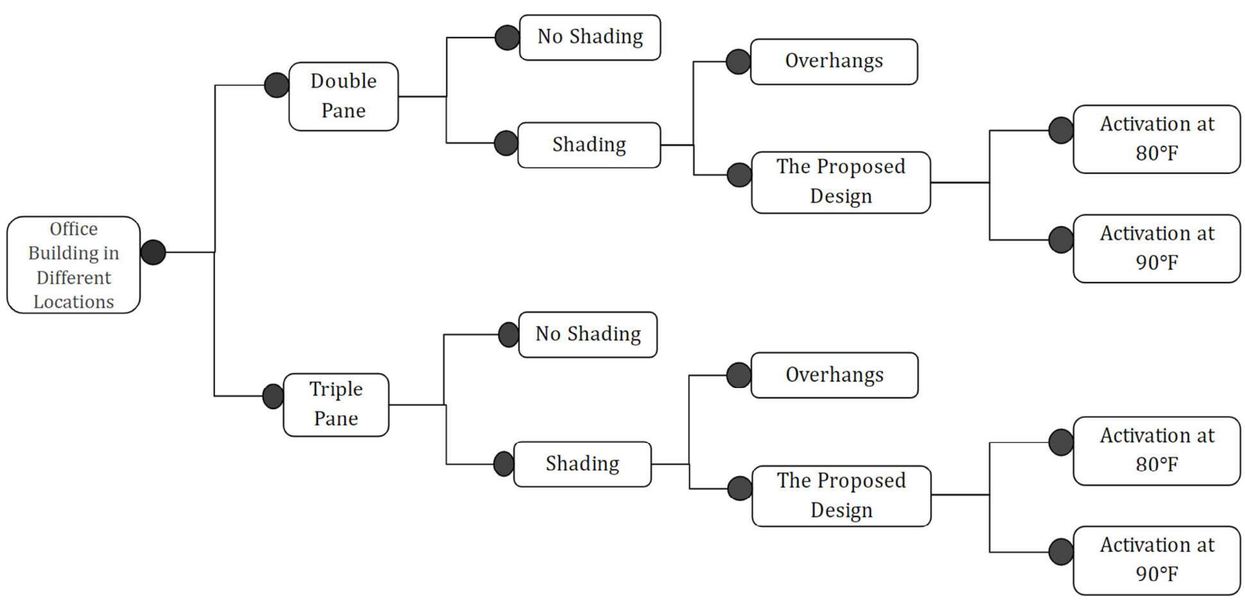


Figure 14- *Different Factors Considered in the Simulations*

To begin analyzing which cases are the most relevant to our project, we considered the changes in Energy per Total Building Area within each case from the fixed overhangs to the proposed design shading. These are the main findings:

1. 80-Degree activation temperature yielded less energy usage.
2. Triple-pane windows yielded less energy usage.
3. The design shading scenarios more likely reduce energy usage when only considering the south facade.

The first two findings were expected as the 80-degree Fahrenheit activation means the design shading is closed more often because the operating threshold is lower. Further, a triple pane window provides higher thermal performance regardless of shading.

Comparison to base cases

Table 10- *Design Savings and Overhang Savings for Total Annual Simulations*

Phoenix				
	Double Pane - Activation at 90°F	Double Pane - Activation at 80°F	Triple Pane - Activation at 90°F	Triple Pane - Activation at 80°F
No Shading Baseline	71.32 kBtu	71.32 kBtu	69.17	69.17 kBtu
Overhang Reduction	-4.77%	-4.77%	-4.34%	-4.34%
Design Reduction	-3.28%	-4.91%	-3.56%	-4.81%
Nashville				
	Double Pane - Activation at 90°F	Double Pane - Activation at 80°F	Triple Pane - Activation at 90°F	Triple Pane - Activation at 80°F
No Shading Baseline	71.76 kBtu	71.76 kBtu	69.42 kBtu	69.42 kBtu
Overhang Reduction	-4.35%	-4.35%	-3.96%	-3.96%

Design Reduction	-2.84%	-4.72%	-3.23%	-4.78%
Worcester				
	Double Pane - Activation at 90°F	Double Pane - Activation at 80°F	Triple Pane - Activation at 90°F	Triple Pane - Activation at 80°F
No Shading Baseline	78.41 kBtu	78.41 kBtu	75.08 kBtu	75.08 kBtu
Overhang Reduction	-2.68%	-2.68%	-2.44%	-2.44%
Design Reduction	0.00%	-2.97%	-1.58%	-4.08%

Table 10 highlights the scenarios in which our design shading had more total energy savings than overhangs. These scenarios are represented above by the percentage of kBTU savings produced by the design in comparison to No Shading. This only occured when the activation temperature was 80 degrees Fahrenheit in all locations.

Table 11- *Percent Savings Difference between all Design and Overhang Cases*

Phoenix				
	Double Pane - Activation at 90 °F	Double Pane - Activation at 80 °F	Triple Pane - Activation at 90 °F	Triple Pane - Activation at 80 °F
Total %	1.56%	-0.15%	0.82%	-0.50%
West %	1.62%	1.45%	0.82%	0.68%
South %	-0.52%	-0.67%	-1.39%	-1.52%
East %	0.71%	-0.26%	-0.22%	-1.01%
Nashville				
	Double Pane - Activation at 90°F	Double Pane - Activation at 80°F	Triple Pane - Activation at 90°F	Triple Pane - Activation at 80°F
Total %	1.57%	-0.39%	0.76%	-0.85%
West %	1.61%	1.37%	0.77%	0.58%
South %	-0.45%	-0.68%	-1.41%	-1.62%

East %	0.85%	-0.18%	-0.17%	-1.02%
Worcester				
	Double Pane - Activation at 90°F	Double Pane - Activation at 80°F	Triple Pane - Activation at 90°F	Triple Pane - Activation at 80°F
Total %	2.75%	-0.30%	0.87%	-1.68%
West %	2.15%	0.94%	0.50%	-0.50%
South %	0.08%	-0.77%	-1.55%	-2.28%
East %	0.58%	0.22%	-1.03%	-1.33%

Table 11 highlights the scenarios in which our design led to a larger percentage decrease in total annual building energy compared to the use of fixed overhangs. Like in Table 10, when broken down regarding each side, our design is at its highest level of functioning in comparison to the fixed overhangs when the activation temperature is at 80 degrees Fahrenheit.

In comparing this data, the team decided to move forward with the fourth case evaluated, a triple-pane window with an 80-degree Fahrenheit activation temperature. This is also the most relevant case because our detail drawings for implementation of the design were set in a triple-pane window. Diving into these circumstances yielded additional data regarding end uses of the energy consumed in each simulation.

Table 12- *End Uses that Saw Changes in Energy*

Heating	Variance	End usage varied in each case.
Cooling	Variance	
Fans	Variance	
Pumps	Variance	
Interior Lighting	Constant	End usage had the same values in each simulation due to ASHRAE template consistency.
Interior Equipment	Constant	

Exterior Lighting	No energy	End use never had any energy attributed to it.
Exterior Equipment	No energy	
Heat Rejection	No energy	
Humidification	No energy	
Heat Recovery	No energy	
Water Systems	No energy	
Refrigeration	No energy	
Generators	No energy	

In Table 12, the end uses are the potential uses of all the energy consumed in a building. This breakdown is an exhaustive list of what system each Btu ends up in. Those labeled "No energy" had 0 kBtu dedicated to them in each simulation. Those labeled "Constant" had the same values in each simulation because they ran on the same ASHRAE template schedule. Those labeled "Variance" had changes in numbers and are expanded upon below.

Table 13- *Annual Breakdown per End Uses*

End Use	Arizona			Nashville			Worcester		
	No Shading Total EUI*	Overhang %	Design %	No Shading Total EUI*	Overhang %	Design %	No Shading Total EUI*	Overhang %	Design %
Heating	11.60	7.7%	-5.3%	13.71	8.7%	-4.3%	29.86	6.7%	-3.6%
Cooling	27.22	-10.9%	-7.4%	25.64	-11.8%	-8.0%	16.16	-17.6%	-9.1%
Fans	8.38	-11.0%	-8.2%	8.10	-11.4%	-8.3%	7.11	-14.0%	-7.3%
Pumps	0.06	-9.8%	-7.2%	0.05	-10.8%	-7.6%	0.03	-12.6%	-7.0%
Total	69.18			69.43			75.08		

*Units kBTU/sf

As seen in Table 13, it is clear that our design is more beneficial to a building in the winter months, as the shading is not activated or shut. In contrast, a fixed overhang is in effect year-round. In terms of heating load, the presence of overhangs actually increases the load versus our mid-pane shading which decreases it. We also ran simulations for a typical week in the summer and the winter as shown below in Tables 14 and 15. In DesignBuilder, the "typical" weeks for simulations are those that the weather database has deemed as standard for the entire season of winter and summer. They are an average snapshot of the whole season.

Table 14- *Winter Typical Week Breakdown per End Uses*

End Use	Arizona			Nashville			Worcester		
	No Shading Total EUI*	Overhang %	Design %	No Shading Total EUI*	Overhang %	Design %	No Shading Total EUI*	Overhang %	Design %
Heating	0.59	6.0%	-4.4%	0.62	3.2%	-2.6%	1.58	2.4%	-2.6%
Cooling	0.39	-11.4%	-8.5%	0.22	-16.5%	-10.7%	0.11	-13.8%	-9.5%
Fans	0.16	-10.4%	-8.0%	0.16	-11.1%	-8.1%	0.15	-11.6%	-6.6%
Pumps	0.00039	-8.0%	-9.5%	0.00028	-7.2%	-6.8%	0.00044	-0.3%	-4.2%
Total	1.57			1.28			0.53		

*Unit is kBTU

Table 15- *Summer Typical Week Breakdown per End Use*

End Use	Arizona			Nashville			Worcester		
	No Shading Total EUI*	Overhang %	Design %	No Shading Total EUI*	Overhang %	Design %	No Shading Total EUI*	Overhang %	Design %
Heating	0.00	0.0%	0.0%	0.00	0.0%	0.0%	461.50	-3.2%	-36.6%
Cooling	68112.06	-8.9%	-6.6%	61258.51	-9.7%	-6.9%	48306.99	-13.4%	-6.4%
Fans	16372.26	-11.2%	-8.3%	15458.18	-11.9%	-8.5%	13176.70	-15.8%	-7.7%
Pumps	226.69000	-8.6%	-6.5%	180.22000	-9.8%	-7.1%	96.12000	-15.7%	-7.3%
Total	1.27			1.20			1.04		

*Unit is kBTU

5. Discussion

Following the analysis of the results, the proposed design was proven as a functioning concept for the integration of smart materials into building components as an energy saving initiative. Based on evolving materials and ideas, the proposed system offers many future opportunities for investigation of the active concepts and optimization of smart material mechanics.

5.1 Overall Discussion of Proposed System

5.1.1 Uncompromised Structural Forces

Structural engineers have a consistent goal to achieve strength and serviceability. After analyzing the overall added weight to the building from the addition of the shading device, the initial structural design remains uncompromised in terms of both strength and serviceability. Using the LRFD method, the calculated 6.34% increase in weight for the facade is well below the margin of uncertainty.

Not only is the added weight of the shading device rather insignificant relative to the overall dead loads for the building, the internal axial deformation acting on the joints of the frame that house the shading device is negligible for most applications. Comparing the magnitude of the axial deformation acting in the joints with the simple bolt hole geometry from the AISC it is clear the 0.35 mm of deformation on the joints is also insignificant.

5.1.2 Proposed Design Shading Efficiency

The prototype developed does not have 100% functionality for several reasons. The calculations performed to solve for the required spring constant to counteract the Nitinol's effects are idealized and the deviations from the ideal include frictional effects and changes in the stiffness of the Nitinol due to the possibility of having an intrinsic elastic modulus that may change with temperature. Further, the heat application for the prototype is slightly different than the building application. This prototype is heated within the acrylic enclosure with a heat lamp. The Nitinol elements are ultimately heated to the same temperature that they would if warmed with solar heat gain; however, this heating process does not follow the same patterns and heat transfer mechanisms that would occur during an actual implementation. For this reason, the factor of time is not accurate when considering the prototype. It cannot be said that this prototype is being heated at the same rate as when installed in a building's facade; therefore, the rate at which the shading closed is not comparable. Despite this, the displacement due to the Nitinol and spring counteraction is directly comparable as the ratio is the same.

Although some prototype elements can be improved, it can be concluded that even with partial functionality, the overall impact of shading provided is still significant. When the prototype is completely activated, it serves about three times the amount of shading compared to a triple-pane window with no shading mechanism. Additionally, the potential for altering the shading material would have a great impact on the occupant's view as well.

5.1.3 DesignBuilder Energy Simulations

The numerical results of the Design-Builder simulations provided emerging evidence that our design performs comparable to current fixed shading practices. The largest takeaways are that

- The proposed design is more effective than overhangs on the south facade.

- The proposed design is more effective than overhangs when activated at a lower temperature.
- The proposed design is more effective than overhangs in terms of heating load.

There are several reasons that lead to these conclusions in addition to the numerical data provided by DesignBuilder.

When the shading was only applied to the south facade of the model, our design ranged from .45% to 2.28% more total annual savings than overhangs in 15 out of 16 cases as seen in Table 10 of Section 4.3. This is attributed to the angle of the sun, rendering the overhangs less useful on the south side. The benefit of our design is that it lies parallel to the plane of the window, so it blocks the sun at any angle. Following this trend, the east and west facades did not have as many instances where our design had a higher percentage of savings than the overhangs. Despite these variations in comparison to overhangs, our design had energy savings in every scenario in comparison to the baseline.

The second point is due to a very obvious fact: the lower the activation temperature, then the more often the design shading is in effect, which furthers its benefits. In real life application, the Nitinol coil can be altered to be activated at different temperatures. Even though simulations were run with different activation temperatures, any of them could be relevant in a real-life application.

The third point is based off of Tables 12, 13, and 14 in Section 4.3. When breaking down due to end use, it is easier to see exactly why our design is more beneficial in certain cases. Interestingly, the components where our design resulted in significantly better annual energy savings were with the heating loads. The addition of fixed overhangs actually increased the heating loads, but the addition of our design reduced the heating loads. This is because our device is only activated in the summer when it is warm enough to activate the Nitinol. The overhangs are always in effect, which reduces the desirable solar heat gain in the winter months.

In conclusion, DesignBuilder results show overall energy savings of fixed overhangs is slightly higher. However, the proposed design's benefits over fixed shading reach farther than energy consumption. Our design is legitimately more beneficial in the winter months. It also provides an architectural design element that can be implemented to alter the visual effects for the building's inhabitants. The concept of this design can have many possibilities to be applied differently in any scenario and be customized for many different buildings.

5.2 Investigating Optimization of Proposed System

The completion of this design is proof of the potential for the integration of Smart Materials into the built environment. While current market solutions limit design and application, as further research and production in this field occur the opportunities for incorporation expand exponentially.

This design was heavily impacted by material availability and acquisition. Throughout the design and testing process, we were limited in our choice in materials due to budget and current market solutions. These solutions were not always fitting with what was found as the ideal characteristics determined through our analyses. These limitations forced the use of replacements that ultimately had an impact on the function and efficiency of the design. Acquisition was another driving factor in our design process, especially with Nitinol. In the early stages of designing we investigated the use of different shapes and transitions of Nitinol. This investigation included a look into two-way SMA that could be trained to return to two different shapes, each related to a unique transition temperature. As this specific alloy is less utilized and rarer, it is associated with a significantly higher cost. We also investigated different shaped Nitinol in the form of a torsion spring. This shape would have allowed for a Chinese Fan like design that was valued for its high efficiency to material ratio and organic feeling motion. These thermo-responsive torsion springs were associated with a long lead time, placing them outside the scope of our future investigations. We also briefly investigated the use of different alloy composites to alleviate cyclability concerns; however, research on SMA has been primarily focused on Nitinol in the past, making the investigation of other SMAs increasingly difficult.

Further, we originally planned to create a shading device that would incorporate an aperture motion within each unit to provide visual comfort in an active way. However, we simplified this aperture movement to be able to more fully develop the active concepts. Therefore, our first recommendation for further development of this project is to develop our simple shape into a more complex design. This can be done by having custom springs and or a different type of Nitinol that would allow for more leeway when designing. Another recommendation is to conduct further research into the use of Nitinol. We only touched upon the very basics of the material at its very beneficial cyclic behavior. Due to advances in technology, Nitinol is becoming a great tool in any engineer's toolbox.

An additional recommendation for future research of the proposed system is to use other parametric design tools to analyze its impacts on the building. DesignBuilder was an adequate tool for an elementary analysis of the proposed system. However, other programs, such as eQuest, have more sophisticated building energy use simulation tools that better address the building performance with a proposed system.

Our device is just a first step to an effective shading device for a building. As research continues to be done on new materials and environmental sustainability becomes more and more prevalent, these ideals will impact the future of architectural engineering design.

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Appendix A - Design Process

This design utilized a screen material cut into a triangular shape connected to a rectangular wooden frame. The tip of the triangle was connected to both the elastic band (in this model the elastic band shown is acting as a spring) and the Nitinol. The mechanism allowed the material to stretch when the Nitinol was heated, and as the Nitinol cooled the elastic band pulled the screen back to the original shape creating an opening that we could not achieve with the previous design. However, we encountered another challenge, the spring helped with the pulling pack of the screen material but the change in length was not drastic. How can we improve this design to create a better more drastic movement?

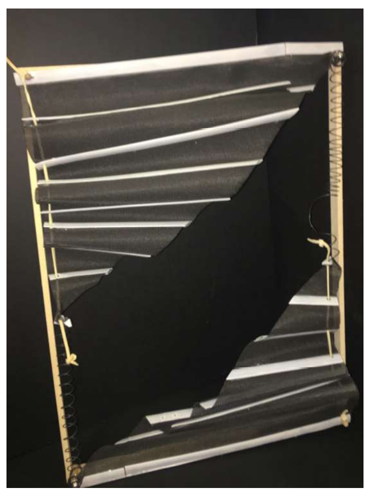


Figure A1 *- Screen Material in a Triangle Accordion Mechanism*

We decided to look into other shapes of Nitinol because so far we only looked into helical springs that only moved in one direction. We came across a torsion Nitinol spring that could potentially be integrated into a material to create a movement. We created a chinese fan inspired design that with the use of torsion springs it would create an organic motion. This design was not further developed due to the fact that torsion springs were not obtainable.

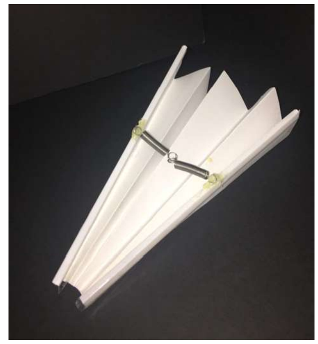


Figure A2- *Torsion Spring(left) Paper in a Chinese Mechanism(right)*

Lastly, we came up with a model with a similar mechanism to the Triangle Accordion design, that also incorporated a pulley interlaced with string. The string was connected on two different sides with the spring and the Nitinol as shown in Figure A3. As the Nitinol was heated up it pulled the string down and unfolding the paper. The springs on the other side was successful at folding back the paper, however, the pulley created a lot of friction that prevented this design from being successful.

Figure A3 - *Paper in a Pulley Mechanism*

MATERIAL

CATEGORY	1	2	3	4
Specific Strength (kNm/kg)	<50	500	1500	>2500

Thermal Conductivity (W/mK)	1 or above	.4 to .99	.07 to .39	0 to 0.07
Thermal Insulator	Low	Medium	High	Excellent/high temperature insulator
Opacity	100%	70%	50%	30%
Solar Heat Gain Coefficient	1	2	3	0.35-0.50
Cost per sqft	>$5	$4.99>x>.50	$.49>x>.21	<$.20
Flammability	Level 3	Level 2	Almost Level 1	Level 1
Solar deterioration	Synthetic material that does not hold up to sun damage for more than 1 year	Holds up for up to 4 years	Holds up for up to 8 years	Material is sealed and understood to be resistant to UV (over 8 years)

MECHANISM

CATEGORY	1	2	3	4
Weight	3 Additional Pieces	2 Additional pieces	One additional piece	Lightweight, spring and wire only
Potential for Failure	High			Low
Obtainable	Difficult (over 20 days)	10-15 days	5 to 10 days	Easy (within 5 days)
Motion	No movement	1 Dimension	2 Dimensions	Unlimited - 3 dimensions
Strength	Not Great			Very strong
Integration	1 or less connections to material	2 connections to material	3 or more connections to material	Embedded in material (many connections)
Length	Hard to Determine			Pre-determined by it
Cost	$50 or more	$49 to 45	$44 to 30	$29 to 0
Scalability	Not feasibly scaled up to real size			Very simple to scale up to full size

Durability	Fails after 1000 uses	Fails after 5000 uses	Fails after 10000 uses	Never fails or breaks

DESIGN

CATEGORY	1	2	3	4
Maintenance due to Failure	Failure of shading material, connection, and SMA	Failure of connection and SMA	Failure of connection	No failure of shading material, connection and SMA
Scale	Has to be one size or shape	Can change size but not shape	Can change the size and shape but not orientation	Change size, shape, and orientation
Innovation	It already exists	Concept and Design exist but combined (ex. lead + eraser > pencil)	Concept exists but design/application is new (ex. laptop or tablet)	It's never been done before and we win a Nobel Prize

Appendix B - Axial Deformation Calculations

NITINOL (Hot)		
W - Applied Load	Newtons	4.17
C - D/d		12.7
n - Active Coil Number		30
G - Modulus of Rigidity	G = E/2(1+v) [MPa]	30384.62
D - Spring Coil Mean Diameter	mm	12.7
d - Diameter of Spring Wire	mm	1
E - Modulus of Elasticity	MPa	79000
v - Poisson's Ratio		0.3
X=	mm	(8WC3n)/GD
X=	mm	0.10

NITINOL (Cool)		
W - Applied Load	Newtons	1.7
C - D/d		12.7
n - Active Coil Number		30
G - Modulus of Rigidity	G = E/2(1+v) [MPa]	13076.92
D - Spring Coil Mean Diameter	mm	12.7
d - Diameter of Spring Wire	mm	1
E - Modulus of Elasticity	MPa	34000
v - Poisson's Ratio		0.3
X=	mm	(8WC3n)/GD
X=	mm	0.09

SPRING		
W - Applied Load	Newtons	2.8
C - D/d		43.47826087

n - Active Coil Number		66
G - Modulus of Rigidity	G = E/2(1+v) [MPa]	77200
D - Spring Coil Mean Diameter	mm	10.00
d - Diameter of Spring Wire	mm	0.23
E - Modulus of Elasticity	MPa	193000
v - Poisson's Ratio		0.25
X=	mm	(8WC3n)/GD
X=	mm	0.2497859878

	Condition	Axial Deformation (mm)
Overall X =	Nitinol - Hot	**0.35**
Overall X =	Nitinol - Cool	**0.34**

Appendix C - System Weight Calculation

Base Model	
Total Base Weight (kg):	**200**

Our Model		
Element	**Quantity**	**Base Weight (kg)**
Paper	2	0.223
Nitinol	2	0.013
Springs	2	0.0049748
Shading Guides	14	0.0052598
Crimps	2	0.00004
Total Added Weight per Model:		0.2462746
Total Added Weight per Window:		2.9552952

Our Window		
Element	**Quantity**	**Base Weight (kg)**
Screws (8-32 .1437 Thick, .5" Long)	8	0.0145
Steal Sherring Strip (.5" wide, .125" deep)	11	9.72
Total Added Weight per Window:		9.7345

Total Added Weight Per Window
12.6897952
Percentage of added weight
6.34%

Appendix D - Completed DesignBuilder Simulations Results

CASES		Energy Per Total Building Area (kBtu/ft2)	Electricity Intensity (kBtu/ft2)	Electricity (kBtu)	Total Site Energy (kBtu)
PHOENIX, AZ	No Shading Total	71.32	58.98	5898325.51	7132257.74
double pane	Fixed Shading Total	67.92	54.61	5461500.8	6792956.2
90 deg	Fixed Shading West	69.14	56.77	5677264.85	6914517.23
	Fixed Shading South	71.17	58.2	5820521.89	7117571.16
	Fixed Shading East	70.36	57.82	5782249.99	7036217.53
	Design Shading Total	68.98	56.86	5686700.77	6898784.92
	Design Shading West	70.26	58.02	5802956.91	7026670.41
	Design Shading South	70.8	58.5	5850962.29	7080296.95
	Design Shading East	70.86	58.57	5857268.64	7087156.82
Phoenix, AZ	No Shading Total	71.32	58.98	5898325.51	7132257.74
Double pane	Fixed Shading Total	67.92	54.61	5461500.8	6792956.2
80 DEG	Fixed Shading West	69.14	56.77	5677264.85	6914517.23
	Fixed Shading South	71.17	58.2	5820521.89	7117571.16
	Fixed Shading East	70.36	57.82	5782249.99	7036217.53
	Design Shading Total	67.82	55.79	5579378.83	6783074
	Design Shading West	70.14	57.91	5791737.99	7015028.54
	Design Shading South	70.69	58.4	5840669.84	7069516.56
	Design Shading East	70.18	57.94	5794317.48	7018312.89

Phoenix	No Shading Total	69.17	57.57	5757723.77	6917905.65
Triple Pane	Fixed Shading Total	66.17	53.68	5368540.86	6617756.77
90 DEG	Fixed Shading West	67.19	55.56	5556408.79	6719589.43
	Fixed Shading South	69.09	56.92	5692508.24	6910030.36
	Fixed Shading East	68.35	56.56	5656335.81	6835221.34
	Design Shading Total	66.71	55.67	5567486.08	6671657.45
	Design Shading West	67.74	56.6	5660908.53	6774753.65
	Design Shading South	68.13	56.96	5696370.65	6813936.75
	Design Shading East	68.2	57.01	5701956.19	6820212.5
Phoenix	No Shading Total	69.17	57.57	5757723.77	6917905.65
Triple Pane	Fixed Shading Total	66.17	53.68	5368540.86	6617756.77
80 DEG	Fixed Shading West	67.19	55.56	5556408.79	6719589.43
	Fixed Shading South	69.09	56.92	5692508.24	6910030.36
	Fixed Shading East	68.35	56.56	5656335.81	6835221.34
	Design Shading Total	65.84	54.85	5485924.22	6584723.66
	Design Shading West	67.65	56.52	5652351.02	6765915.06
	Design Shading South	68.04	56.87	5687618.18	6804780.64
	Design Shading East	67.66	56.52	5652841.77	6766296.36

CASES	Energy Per Total Building Area (kBtu/ft2)	Electricity Intensity (kBtu/ft2)	Electricity (kBtu)	Total Site Energy (kBtu)

Nashville, TN	No Shading Total	71.76	57.15	5715138.25	7176845.32
double pane	Fixed Shading Total	68.64	52.7	5270190.5	6864466.08
90 deg	Fixed Shading West	69.57	54.81	5481271.85	6957624.56
	Fixed Shading South	71.61	56.26	5626588.16	7161955.19
	Fixed Shading East	70.89	55.99	5599291.52	7089464.18
	Design Shading Total	69.72	55.23	5523539.07	6972719.08
	Design Shading West	70.69	56.14	5614811.27	7070097.63
	Design Shading South	71.29	56.7	5670799.69	7129758.55
	Design Shading East	71.49	56.89	5689882.67	7150012.83
Nashville	No Shading Total	71.76	57.15	5715138.25	7176845.32
double pane	Fixed Shading Total	68.64	52.7	5270190.5	6864466.08
80 deg	Fixed Shading West	69.57	54.81	5481271.85	6957624.56
	Fixed Shading South	71.61	56.26	5626588.16	7161955.19
	Fixed Shading East	70.89	55.99	5599291.52	7089464.18
	Design Shading Total	68.37	53.93	5393684.41	6837874.17
	Design Shading West	70.52	55.97	5597784.37	7052624.52
	Design Shading South	71.12	56.54	5654485.66	7112851.1
	Design Shading East	70.76	56.2	5621042.48	7077041.84
Nashville	No Shading Total	69.42	55.71	5571382.25	6942503.81
Triple	Fixed Shading Total	66.67	51.77	5177293.8	6667780.9
90 deg	Fixed Shading West	67.43	53.59	5359128.62	6743393.89
	Fixed Shading South	69.34	54.98	5498641.41	6935004.65
	Fixed Shading East	68.65	54.69	5470030.29	6865741.07
	Design Shading Total	67.18	54.02	5402380.34	6718525.04
	Design Shading West	67.95	54.75	5475224.99	6795508.03
	Design Shading South	68.36	55.13	5513989.49	6836546.71
	Design Shading East	68.53	55.3	5530445.75	6854055.19
Nashville	No Shading Total	69.42	55.71	5571382.25	6942503.81
triple pane	Fixed Shading Total	66.67	51.77	5177293.8	6667780.9
80 deg	Fixed Shading West	67.43	53.59	5359128.62	6743393.89

	Fixed Shading South	69.34	54.98	5498641.41	6935004.65
	Fixed Shading East	68.65	54.69	5470030.29	6865741.07
	Design Shading Total	66.1	52.98	5298980.65	6610911.24
	Design Shading West	67.82	54.62	5462889.01	6782871.06
	Design Shading South	68.22	55	5500429.14	6822334.88
	Design Shading East	67.95	54.75	5475634.19	6795609.93

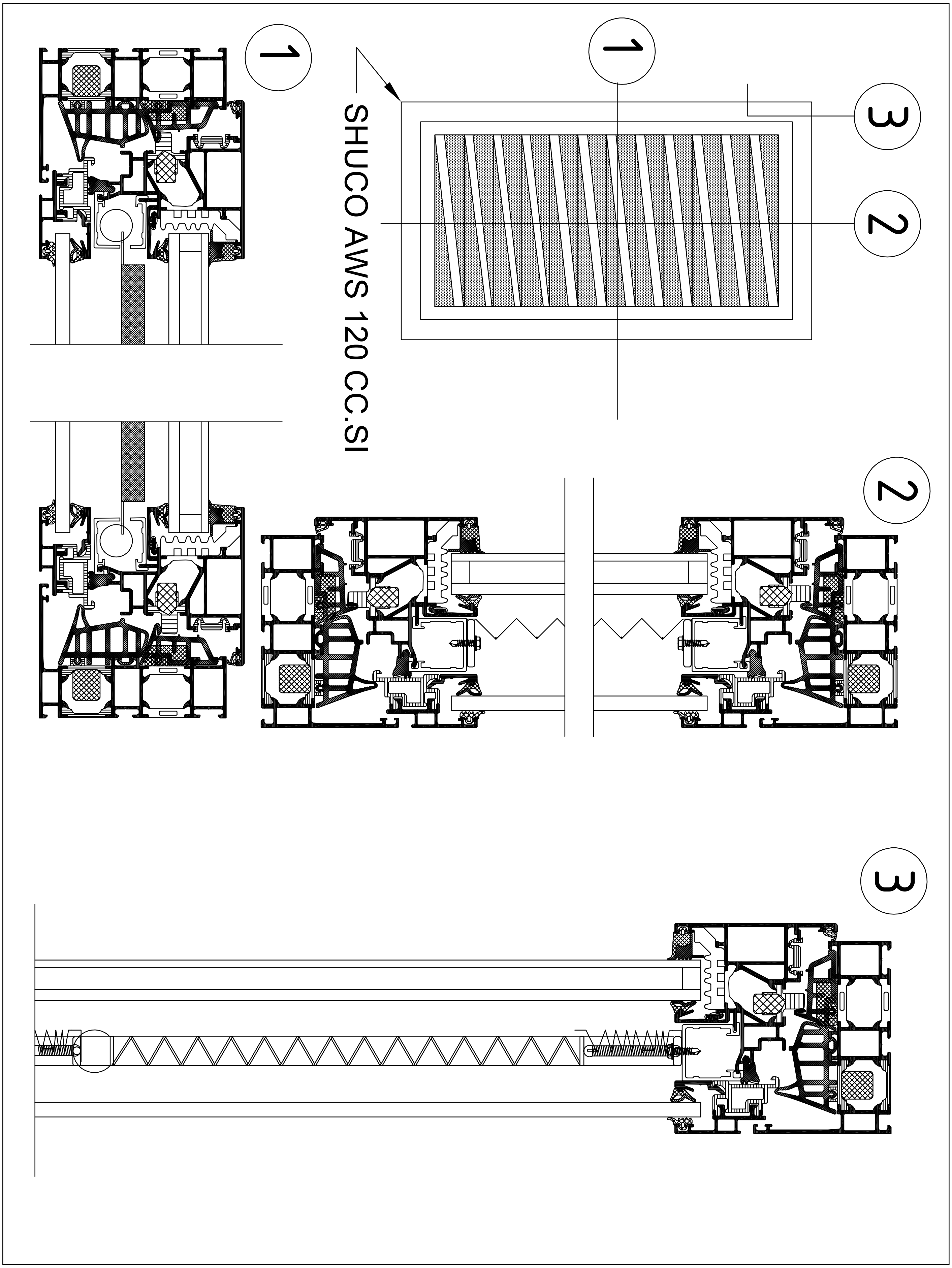
CASES		Energy Per Total Building Area (kBtu/ft2)	Electricity Intensity (kBtu/ft2)	Electricity (kBtu)	Total Site Energy (kBtu)
Worcester, MA	No Shading Total	78.41	46.49	4649017.74	7842094.12
double pane	Fixed Shading Total	76.31	42.14	4214772.14	7631310.04
90 deg	Fixed Shading West	76.76	44.47	4447260.46	7677144.91
	Fixed Shading South	78.35	45.27	4527109.81	7835965.07
	Fixed Shading East	77.96	45.49	4549744.49	7796612.93
	Design Shading Total	78.41	46.48	4648727.94	7841812.01
	Design Shading West	78.41	46.48	4648920.47	7842000.37
	Design Shading South	78.41	46.48	4648909.45	7841987.93
	Design Shading East	78.41	46.49	4648959.17	7842036.67
worcester	No Shading Total	78.41	46.49	4649017.74	7842094.12
double pane	Fixed Shading Total	76.31	42.14	4214772.14	7631310.04
80 deg	Fixed Shading West	76.76	44.47	4447260.46	7677144.91
	Fixed Shading South	78.35	45.27	4527109.81	7835965.07
	Fixed Shading East	77.96	45.49	4549744.49	7796612.93
	Design Shading Total	76.08	44.28	4428816.23	7608607.57
	Design Shading West	77.48	45.6	4559982.6	7748940.89
	Design Shading South	77.75	45.85	4585356.13	7776038.71
	Design Shading East	78.13	46.21	4621717.14	7813581.86
worcester	No Shading Total	75.08	45.22	4521976.43	7508332.03

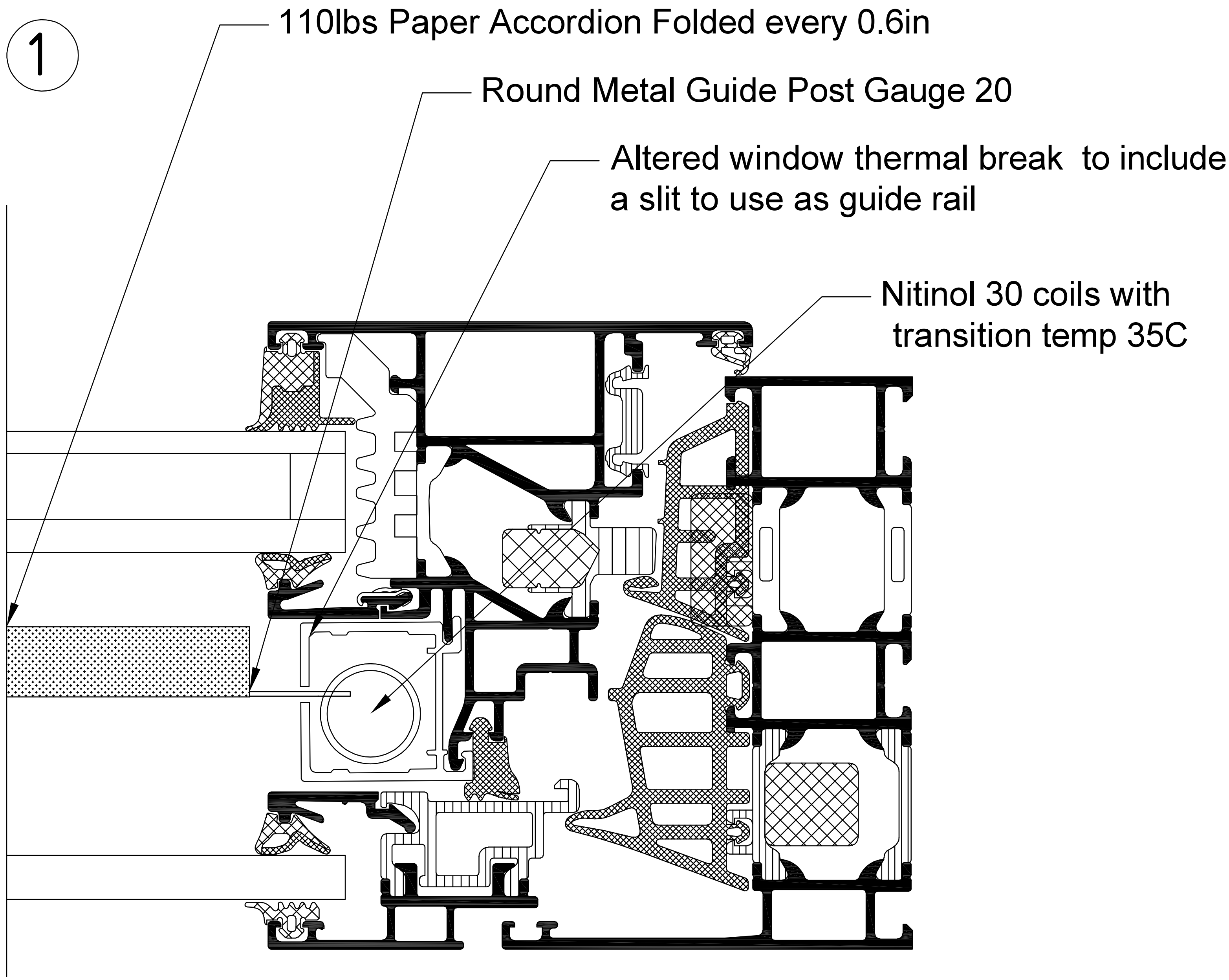
Triple	Fixed Shading Total	73.25	41.38	4138156.1	7325925.67
90 deg	Fixed Shading West	73.52	43.32	4332672.13	7352368.79
	Fixed Shading South	75.05	44.17	4417721.81	7505956.93
	Fixed Shading East	74.66	44.33	4433618.7	7466675.78
	Design Shading Total	73.89	45.02	4502035.9	7389544.11
	Design Shading West	73.89	45.02	4502179.69	7389685.66
	Design Shading South	73.89	45.02	4502166.63	7389671.75
	Design Shading East	73.89	45.02	4502205.97	7389710.51
worcester	No Shading Total	75.08	45.22	4521976.43	7508332.03
triple pane	Fixed Shading Total	73.25	41.38	4138156.1	7325925.67
80 deg	Fixed Shading West	73.52	43.32	4332672.13	7352368.79
	Fixed Shading South	75.05	44.17	4417721.81	7505956.93
	Fixed Shading East	74.66	44.33	4433618.7	7466675.78
	Design Shading Total	72.02	43.23	4323691.4	7203118.76
	Design Shading West	73.15	44.31	4430943.57	7315713.74
	Design Shading South	73.34	44.49	4449509.6	7335038.64
	Design Shading East	73.67	44.8	4480800.9	7367787.2

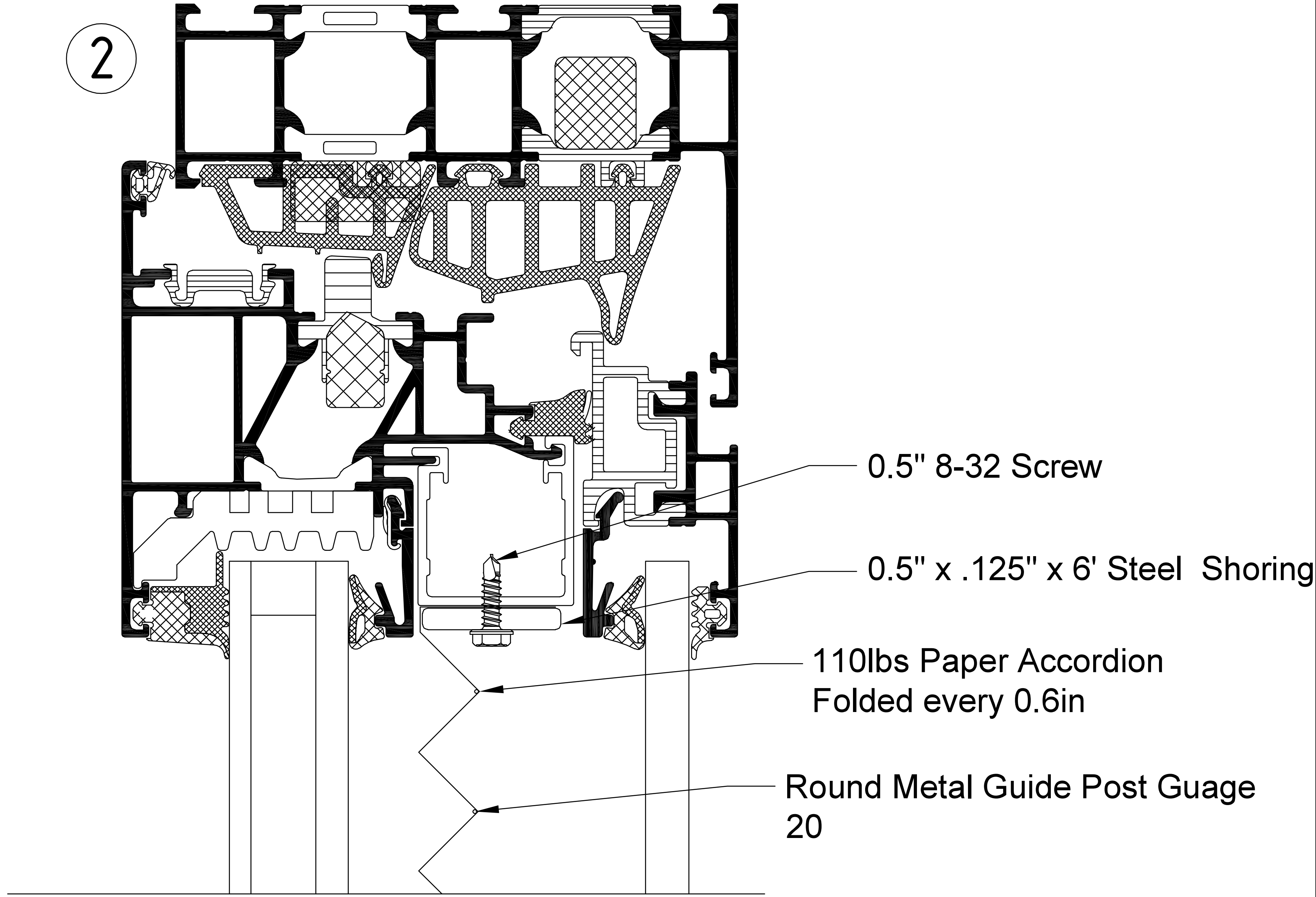
Appendix E - Prototype Data Collection

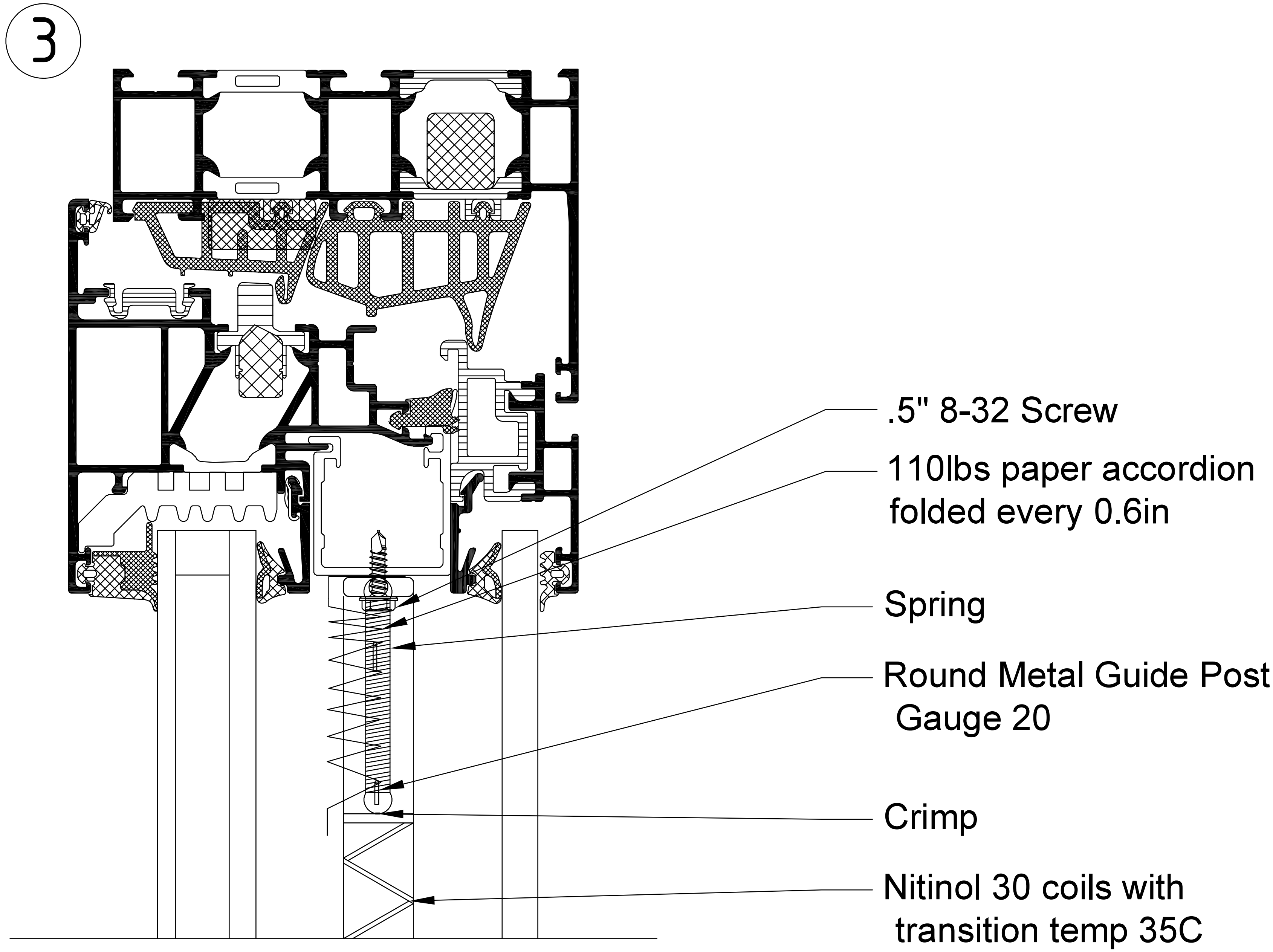
	Displacement (Inches)	Reaction Time (When heat activated) (Min:Sec)	Reaction Time (When heat is deactivated) (Min:Sec)
Trial 1	6 3/8	4:21	5:55
Trial 2	6 1/4	4:29	6:04
Trial 3	6	4:24	5:58
Average	6 1/4	4:25	5:58
Percent Closed	60%		

Appendix F-Detail Drawings




1
110lbs Paper Accordion Folded every 0.6in
Round Metal Guide Post Gauge 20
Altered window thermal break to include a slit to use as guide rail
Nitinol 30 coils with transition temp 35C


2
0.5" 8-32 Screw
0.5" x .125" x 6' Steel Shoring
110lbs Paper Accordion
Folded every 0.6in
Round Metal Guide Post Guage
20


3
.5" 8-32 Screw
110lbs paper accordion
folded every 0.6in
Spring
Round Metal Guide Post
Gauge 20
Crimp
Nitinol 30 coils with
transition temp 35C