Design and Fabrication of Shape Memory Alloy–Actuated Butterfly Tiles for Adaptive Thermal Regulation

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M.Eng Report

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Abstract

This project looks at whether soft, butterfly-shaped silicone tiles can be moved using shape memory alloys (SMAs) for adaptive thermal regulation. The butterfly shape allows the surface area to change a lot with only small movements at the edges, which could help control airflow and heat passively. At first, the team tried using rigid mechanical linkages to move the structure, but tests showed that rigid parts did not work well with the flexible silicone. Because of this, the design switched to using Nitinol SMA springs, which were attached to EcoFlex butterflies. Several prototypes were made with molded silicone and 3D-printed tools. The team tested SMA springs with different shapes by activating them with heat and electricity. The results showed that the SMA springs could contract reliably at low voltages and currents, but there were problems with heat loss, overheating, and not enough force to return the tiles to their original shape. While fully reversible movement was not achieved, the project identified important mechanical, thermal, and electrical limits for using SMAs in soft systems.

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Acknowledgements

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Introduction

Researchers are increasingly interested in adaptive systems that control airflow and heat by changing their shape. Instead of using rigid parts and standard motors, recent studies have looked at soft, lightweight structures that move because of their material properties. This project continues earlier lab work on bio-inspired designs that use butterfly-shaped patterns as adaptive thermal elements. The butterfly shape allows for big changes in surface area with only small movements at the edges, which makes it useful for controlling airflow by opening and closing. The main goal was to see if these butterfly tiles could move using shape memory alloys (SMAs) placed in or on soft silicone, instead of using rigid mechanical parts. At first, the project tried using a mechanical linkage system to fold the butterfly wings. But early prototypes showed problems when combining rigid parts with flexible materials, such as too much weight, stress in certain areas, and weak connections to the soft silicone. Because of these issues, the team switched to using SMAs, the original idea, which are lightweight, powerful for their size, and operate quietly with Nitinol wires and springs, as seen in the initial sketches in Figure #1. This work looks mainly at design changes, ways to make the tiles, and whether they can be moved as planned, not at automatic control or long-term use. By building different prototypes, testing materials, and running electrical actuation experiments, the project examines the real-world challenges of adding SMAs to soft butterfly tiles. The findings help explain the mechanical, thermal, and electrical factors that affect how well these SMA-powered adaptive systems work.

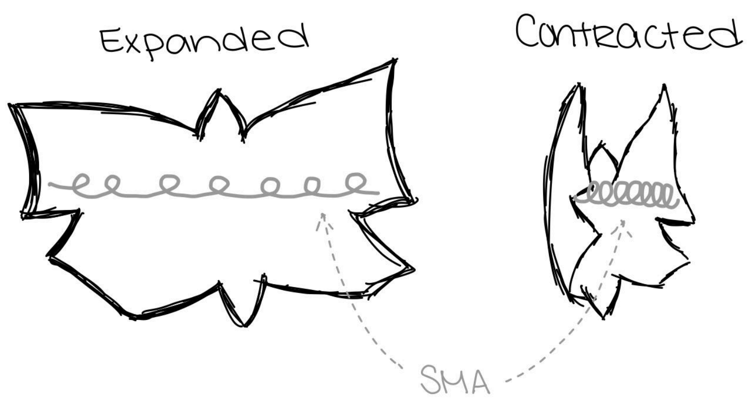

Figure #1: *Initial sketches of the expanding/contracting mechanism with SMAs*

Background

SMAs are often used as actuators in adaptive and smart structures because they can change shape and have a high force-to-weight ratio [2], [3], [4]. Studies have shown that SMAs can be built into morphing micro-aircraft and other devices that change shape, where electrical control allows them to adapt their form [1]. These examples show how SMAs could possibly be used in soft adaptive surfaces, like the butterfly tiles studied in this project.

Rigid actuators like motors and linkages are effective in stiff structures but are hard to use with soft materials. Their weight and stiffness can restrict movement, create stress points, and make attachment difficult. As a result, material-based actuation has become a popular choice for soft systems. SMAs, such as Nitinol, change shape when heated and can contract toward a preset form. SMAs offer a high force-to-weight ratio and can be added to soft systems without much extra weight. However, their performance depends on electrical input, heat loss, and how well they are anchored, all of which need careful control in flexible systems. This project looks at whether butterfly-shaped silicone parts can be reliably moved using SMAs and identifies the main challenges when combining smart materials with very flexible bases.

Theory

Shape memory alloys can switch back and forth between martensite and austenite phases. At low temperatures, they stay in a flexible martensitic state, which lets them be deformed. When heated past their transition temperature, they change to the austenitic phase and recover their pre-trained shape, producing mechanical work. This thermomechanical behavior, including the roles of twinned and detwinned martensite, during loading and unloading, is demonstrated in Figure #2.

$$P = I^2 * R$$

Where (P) is power, (I) current, and (R) resistance. The resistance of the SMA highly depends on the wire's length, diameter, and shape, which affects the voltage and current needed for actuation. Heat loss to the environment and the base material can lower performance as well, especially when SMAs are combined with insulating materials like silicone. These factors influenced how the experiment was set up and how the results were understood.

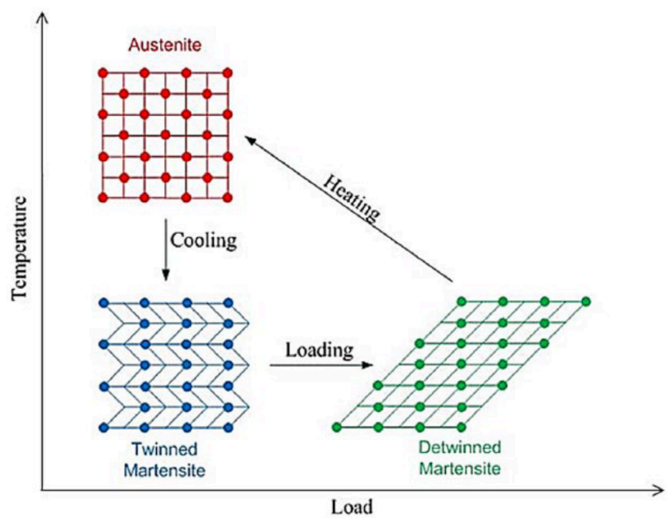

Figure #2: *Schematic of thermomechanical phase transformations in SMAs (Daudpoto, 2015)*

For this project, SMA springs served as surface-mounted actuators that turn electrical energy into mechanical contraction, causing the butterfly wings to bend and fold. The system depends on contraction forces near the wing edges, while the center of the butterfly stays fixed. The EcoFlex substrate provides structure and helps the wings contract with less force, but its low stiffness makes passive reopening difficult. Because of this, where the actuators are placed, the shape of the springs, and the amount of heat applied all influence how much the wings can move and how reliably they do so.

Design and Decision Criteria

The initial design goal was to create a modular butterfly-shaped tile capable of reversible opening and closing for adaptive coverage. Early design criteria included: low-profile actuation, compatibility with soft materials, and scalability to tiled arrays.

Early Mechanical Design: The "El Fiu" Mechanism

The team started by building a rigid mechanical linkage called "el fiu" or boomerang mechanism. Early ideas for the butterfly actuation geometry were inspired by kinetic design work shared on social media, where compliant mechanisms helped create large surface movement with little force [6]. Initial sketches and CAD models were created to explore different lever-arm shapes and pin joints that could convert straight motion into wing motion, as shown in Figs. #3 and #4. Prototypes made from PLA were tested with fabric and resin butterflies. The mechanism worked in a basic way, but the rigid parts turned out to be too heavy and stiff for the softer materials. Stress near the attachment points also caused the resin butterflies to fracture.

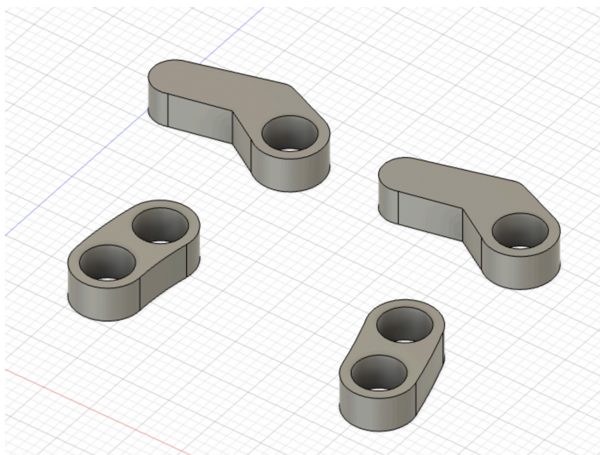

Figure #3: *Initial CAD model of the mechanical linkage used to actuate the butterfly wings.*

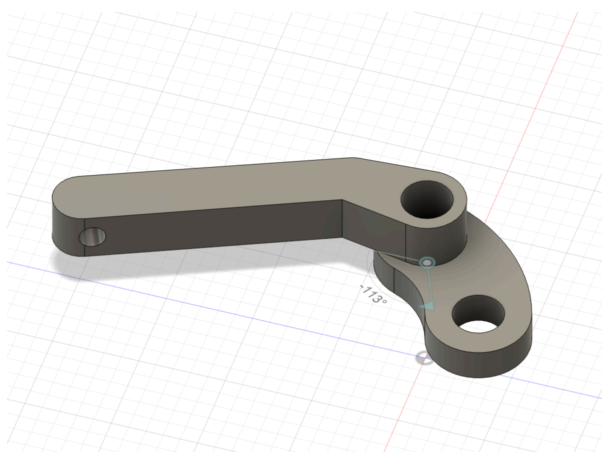

Figure #4: *Final CAD iteration of the mechanical linkage, incorporating an extended lever arm and revised joint geometry*

Material Shift to EcoFlex

The initial material selected for the butterfly tiles was a flexible SLA-printed resin,because it offered high print resolution and could make detailed shapes like thin features. Flexible resins also provided some flexibility while keeping their shape, which was useful for early prototypes. However, several problems came up during fabrication and testing. SLA printing proved time-consuming and resulted in frequent print failures. Post-processing was difficult because rigid resin residues would contaminate the isopropyl alcohol (IPA) station. After curing, the resin would be brittle, and dense support structures would cause surface defects. Flexible resins are also relatively expensive and require extended post-curing procedures to ensure the material is safe for skin contact, an important consideration given the intended wearable nature of the system.

Mechanical problems appeared when the rigid “El Fiu” linkage was added. The linkage worked as planned, but attaching it to the resin butterfly with fasteners caused stress points that the material could not handle. Cracks and failures happened at the fastener–resin interface, as shown in Figure #5. These issues showed that the resin was too brittle for concentrated loads and too stiff to be moved by the available SMA setups without using thicker wires or more power, which would create thermal and electrical risks.

To address these issues, the team switched to EcoFlex silicone elastomer. EcoFlex cost less, was non-toxic, and allowed several tiles to be made at once. Its flexibility made it better for large movements and for working with SMA-based actuation, which uses low force. EcoFlex also prevented brittle failures at attachment points by spreading out the load. The main drawbacks were longer curing times, about four hours per batch, and less detail in shapes compared to SLA printing. Despite these downsides, EcoFlex was a better option for making, using, and safely wearing the butterfly tiles, so it became the final material.

Figure #5: *Failure of the resin butterfly with the mechanical linkage attached*

Design Shift to SMA Actuation

After finding limits with rigid mechanical actuation and seeing that SMA materials were available, the design moved from linkage-based mechanisms to direct SMA actuation. This change was based on how well the materials worked with EcoFlex, as shown in the Results section, and on system-level issues caused by the tessellated butterfly tiles. In a tiled array, the rigid “El Fiu” linkages took up the same space needed for nearby butterflies to open and close, which caused mechanical interference between tiles. This overlap made it hard to scale up and meant the linkage-based approach did not work for tightly packed adaptive surfaces.

Although SMA-based actuation is not always simpler in terms of cost or reliability, it did offer several benefits that matched the project’s goals. SMAs work at low voltages, are flexible, and can be safely used in soft, wearable systems [7]. Also, using direct SMA actuation removed rigid parts that limited movement and caused stress points, so force could be spread more evenly across the butterfly wings.

During development, antagonistic SMA setups were tested but dropped because of thermal cross-talk between opposing actuators and not enough net force when used with very flexible EcoFlex substrates. The design then focused on contraction-only SMA actuation, choosing butterfly thickness to balance curing reliability. While SMAs do raise questions about material fatigue and long-term durability, this work focused on feasibility and integration.

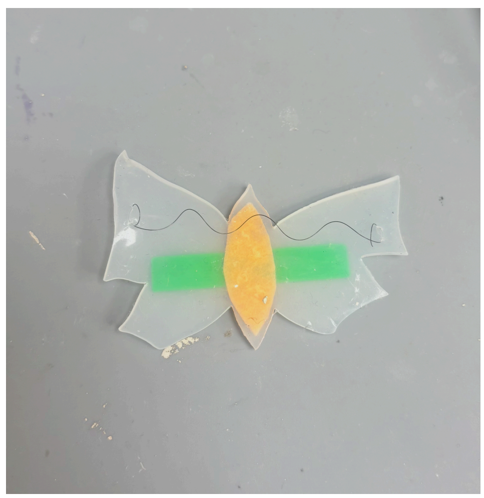

Figure #6: *SMA spring geometry and attachment configuration used to actuate the EcoFlex butterfly*

Materials and Apparatus

Materials and equipment used in this project include:

- Nitinol SMA springs (various mandrel sizes and wire sizes)
- Ecoflex silicone elastomer
- PLA molds fabricated via FDM printing
- Bench DC power supply
- Digital multimeter
- Sil-Poxy silicone adhesive
- Conductive copper wire and crimps
- Heat gun for thermal activation

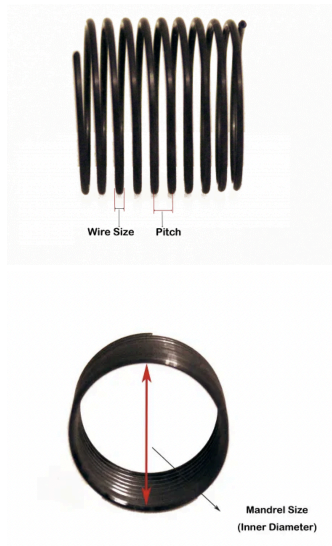

Figure #7: *SMA Helical Springs (Image from Kellogg's Research Lab)*

Procedure

Mold Fabrication and Ecoflex Casting

Butterfly-shaped inverse molds were designed in CAD and made with PLA, as seen in Figure #8, since the SLA printing failed because the supports were too shallow. Ecoflex was mixed according to the manufacturer's instructions and poured into molds with thicknesses of 1 mm, 2 mm, and 3 mm. Only the 3 mm molds cured fully and kept their shape; the other two thicknesses failed by breaking when being removed from the mold.

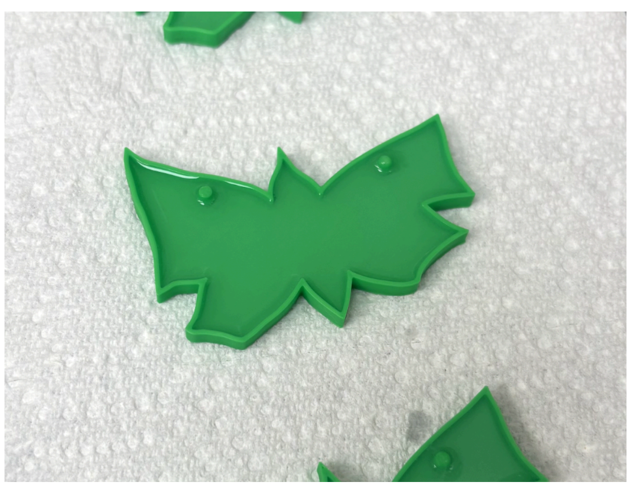

Figure #8: *Butterfly-shaped inverse molds from PLA*

SMA Preparation and Characterization

SMA springs were cut in 6-, 10-, and 15-loop configurations and electrically characterized by measuring resistance with a digital multimeter (Fig. #9). These measurements were used to estimate the voltage and current requirements for actuation. Spring geometry selection was guided by resistance trends and power calculations, as configurations with fewer loops exhibited lower resistance and therefore enabled actuation at lower voltages, see Table 1 in the Appendix. The six-loop SMA spring wound on a 4.75 mm mandrel provided the highest power density while minimizing material usage and was selected for continued testing.

SMA placement was chosen to maximize mechanical effectiveness while preserving the intended structural behavior of the butterfly tile. Positioning the SMA along the wings increased the moment arm relative to the central constrained region, allowing sufficient contraction force to fully close the wings. This configuration also avoided interference with the center of the butterfly, which was designed to remain rigid and fixed during actuation.

Figure #9: *SMA and multimeter setup*

<u>*Actuation Testing*</u>

A heat gun was first used to see if the springs would contract as expected, setup shown in Figure #10. Then, electrical actuation tests were done with a bench power supply, setup seen in Figure #11, by slowly increasing the voltage and observing how the SMA reacted.

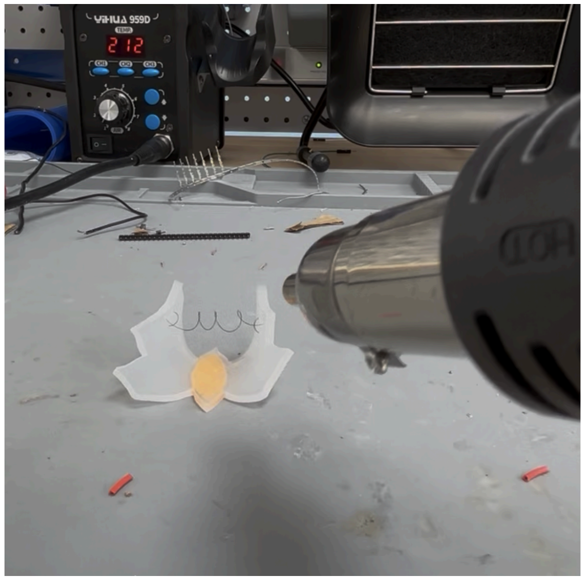

Figure #10: *Heat gun and SMA setup*

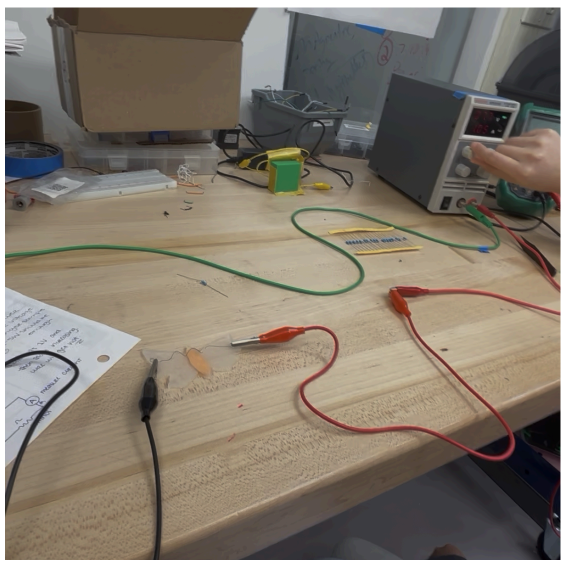

Figure #11: *DC power supply and butterfly with SMA setup*

Work Plan

The project used an iterative development process that included the following steps:

1. Concept sketching and CAD development
2. Mechanical prototyping and testing
3. Material fabrication and failure analysis

4. SMA characterization
5. Electrical actuation experiments
6. Design pivots informed by experimental results

This approach helped us quickly find failure modes and make better design choices in the next steps.

Results

The rigid mechanical actuation with the “el fiu” linkage worked well on stiff substrates but did not succeed with soft EcoFlex butterflies. Figure #12 shows that the extra mass and stiffness of the linkage stopped the wings from fully contracting and caused the flexible silicone to sag.

Testing the SMA springs showed that resistance went up as the number of loops increased. The six-loop springs measured about 7 Ω, while the ten- and fifteen-loop springs measured 18.65 Ω and 25.2 Ω. After calculating power output for common supply voltages, the six-loop SMA spring with a 4.75 mm mandrel was chosen for actuation tests.

SMA contraction during electrical actuation was first seen at about 2 V and 0.2 A, as shown in Figure #13. Raising the voltage above 5 to 7 V caused overheating, visible smoke, and permanent loss of the spring’s trained shape. Using antagonistic SMA setups to expand the wings did not open them enough when attached to EcoFlex substrates.

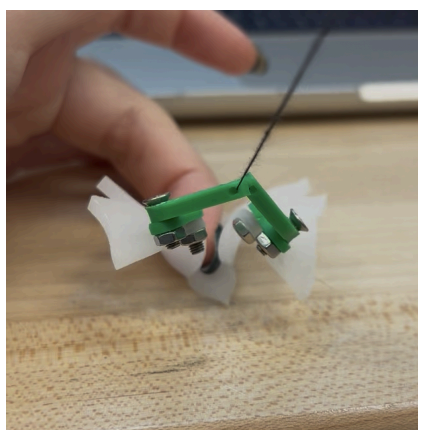

Figure #12: *Mechanical linkage actuator with EcoFlex butterfly*

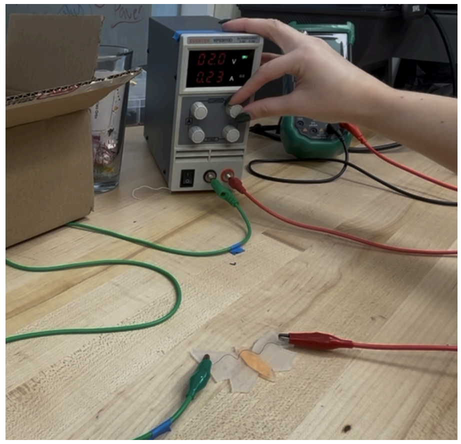

Figure #13: *SMA beginning to contract under electrical actuation at approximately 0.2 A*

Discussion

The experiments show that it is difficult to combine actuation mechanisms with very flexible materials. The mechanical linkage worked well for rigid and semi-rigid substrates, but its weight and stiffness did not suit the EcoFlex butterflies. The linkage caused extra weight and stress at the attachment points, which limited movement and stopped full contraction. This shows that rigid actuation methods do not work well for soft, thin silicone structures.

SMA-based contraction worked better with the EcoFlex butterflies because the wire springs are light and spread out the force. The six-loop SMA setup gave enough contraction at low voltages, showing that electric actuation can change the shape of soft tiles. However, trying to expand the tiles using pairs of opposing SMA springs did not work. Heat from one spring affected the other, and the EcoFlex material was not stiff enough to help the tiles open. Without a strong passive force to help them return, SMA contraction alone could not make the tiles expand and contract in a controlled way.

Thermal and electrical limits also affected how well the system worked. The SMA wires activated at low voltages, but even a small increase in voltage caused them to overheat quickly, which made them lose their trained shape for good. Heat spreading into the silicone made the actuation less efficient, so more power was needed and the safe range for operation became smaller. These results show that careful electrical control and good heat management are important when using SMAs in insulating materials.

In summary, SMA-based contraction can work for soft adaptive tiles, but the overall design needs to consider how flexible the material is, heat loss, and uneven actuation. Adding passive mechanical support or extra structure may be needed to make sure the tiles can move back and forth reliably.

Recommendations

Future work should aim to improve the SMA actuation system and add more features to the butterfly tile array. Testing smaller mandrel SMA springs, especially the 0.15 mm size, is suggested to use less material and lower costs while keeping enough actuation force. This will mean getting more SMA material than what is currently in the lab. It is also worth exploring different SMA setups and attachment points on the butterfly wings. Trying new anchor spots and lever arms could help use less SMA and make the actuation more efficient. Electrical control can be improved by using PWM-based current regulation with a microcontroller, MOSFET, and push-button interface. This setup would give more precise control over heating and make results more consistent. Adding thermistors for real-time temperature feedback would help protect the SMA from heat damage and allow for closed-loop control later. Future work should also look into ways to connect nearby tiles so that several tessellated butterflies can move together across larger surfaces.

Appendix

Presentation with extra videos and pictures

Length	Resistance (ohms)	Voltages (V):	3	5	9	12
6 loops	7	Current (A) =	0.4285714286	0.7142857143	1.285714286	1.714285714
		Power (W) =	1.285714286	3.571428571	11.57142857	20.57142857
10 loops	18.65	Current (A) =	0.1608579088	0.2680965147	0.4825737265	0.6434316354
		Power (W) =	0.4825737265	1.340482574	4.343163539	7.721179625
15 loops	25.2	Current (A) =	0.119047619	0.0283446712	0.3571428571	0.4761904762
		Power (W) =	0.3571428571	0.9920634921	3.214285714	5.714285714

Table #1: *The resistance and power calculations for the three different lengths of the SMA*

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