Designing a Better Hair Straightener

by

Melissa B. Read

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ABSTRACT

The Simply Straight Hair Brush was designed and built. The aim of the Simply Straight Hair Brush was to straighten hair faster and better than any product currently on the market. The current products were studied and the idea for a hair brush with heated bristles was developed. A product and patent search revealed that no idea similar to this existed.

An experiment was performed to determine the relationship between tension, heat, and straightness. A design was formulated. Several heat transfer analyses were performed on this design. A prototype was built and tested for safety.

The brush was then tested on several subjects resulting in significantly straighter hair. However, there was still room for improvement. The second iteration should have an optimized bristle configuration. It should also use a plastic with a higher maximum operating temperature so that the brush can be hotter. A third improvement would be putting in a temperature switch instead of relying on equilibrium for temperature control.

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1 Introduction

For as long as I can remember, I have been trying to make my curly hair straight. I have purchased special brushes, nozzles for my blow dryer, and flat irons. Once I even attempted to permanently, chemically straighten my hair but the treatment did not work. I could not help but thinking that I could make a better product. I decided to attempt to do just that for my undergraduate thesis.

In addition to being an area of personal interest, there is a large consumer demand for hair straightening products. The hair care industry is a multibillion dollar industry [9]. Current straightening products can be costly or take several hours to use. My goal was to create a hair straightener which worked faster and was easier to use than existing products.

The result was the Simply Straight Hair Brush. The user brushes her hair like she would with any other brush, but this brush straightens her hair. The first iteration prototype straightens hair in about the same time as a typical flat iron. The result is not as straight as some existing products; however, I believe a second iteration will be able to create the same results as those products. The second iteration will have an optimized bristle configuration and will operate at a higher temperature.

2 Understanding the Problem: What makes hair straight?

Before making any design decisions, it was first necessary to fully understand the problem. I researched the structure of hair and what caused it to be curly or straight. I also performed a bench level experiment to determine how heat and tension affect hair's straightness.

2.1 The Structure of Hair

Hair has three main structures: the cuticle, the cortex, and the medulla. Figure 1 shows a drawing of these structures.

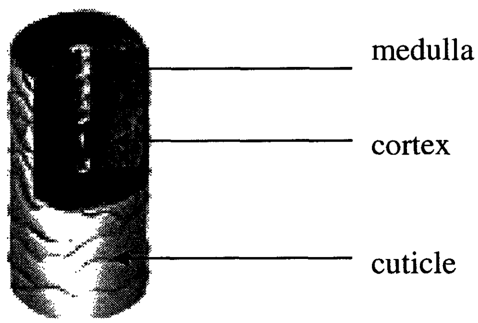

Figure 1: The three main structures of a human hair [6].

The cuticle is the outer most layer of the hair. It consists of layers of flat overlapping cells. The cuticle is generally resistant to chemicals and is the area most often damaged by daily activities, such as brushing hair. The cuticle is shown in figure 2.

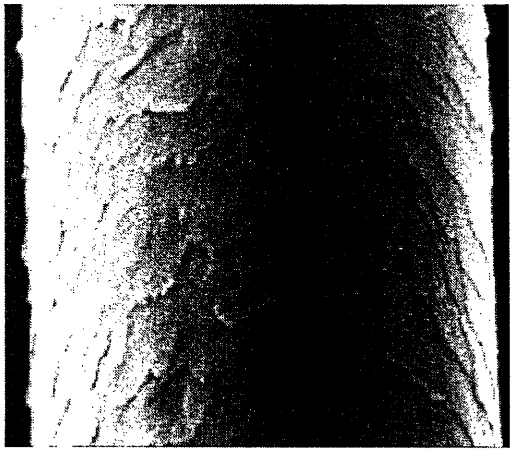

Figure 2: Cuticle cells of a human hair [8].

The bulk of each hair's mass is contained in the cortex. The cortex contains the various proteins and bonds which determine the curliness of straightness of the hair. A picture of the cortex is shown in figure 3.

Figure 3: A damaged human hair revealing the cortex. The cuticle has been ripped off revealing the mass of proteins and other sub structures comprising the cortex [7].

The final structure contained in hair is the medulla. In human hair, the medulla contains only a small fraction of each hair's mass. The medulla is not believed to have any effect on the straightness of human hair. The medulla is more prevalent in stiff hairs, such as like those comprising a porcupine's quills or a horse's tail.

Temporary hair straightening can be achieved by breaking the hydrogen bonds located in the cortex. These bonds kink the hair, causing it to curl. As hydrogen bonds are heated, their resistance to imposed strain decreases [1]. Therefore if hair is heated and a tensile stress is applied, these hydrogen bonds break and the hair looses its curl. However if the hair is exposed to water or humidity, the hydrogen bonds can use the water to reform.

2.2 Finding the Relationship Between Hair and Tension

Robbin's *Chemical and Physical Behavior of Human Hair* states that hair can be temporarily straightened by applying heat and a tensile force. However a numerical relationship between tension and straightness is not provided. That relationship probably varies greatly from person to person since the properties of each person's hair can be so different. Since this design primarily addresses my hair, I decided to do an experiment which would quantify the relationship between straightness and tension in my hair when subjected to a constant heat. This experiment would have to apply constant heat to a single strand of hair. The tension on the hair had to be variable. Figure 4 shows the setup of this experiment.

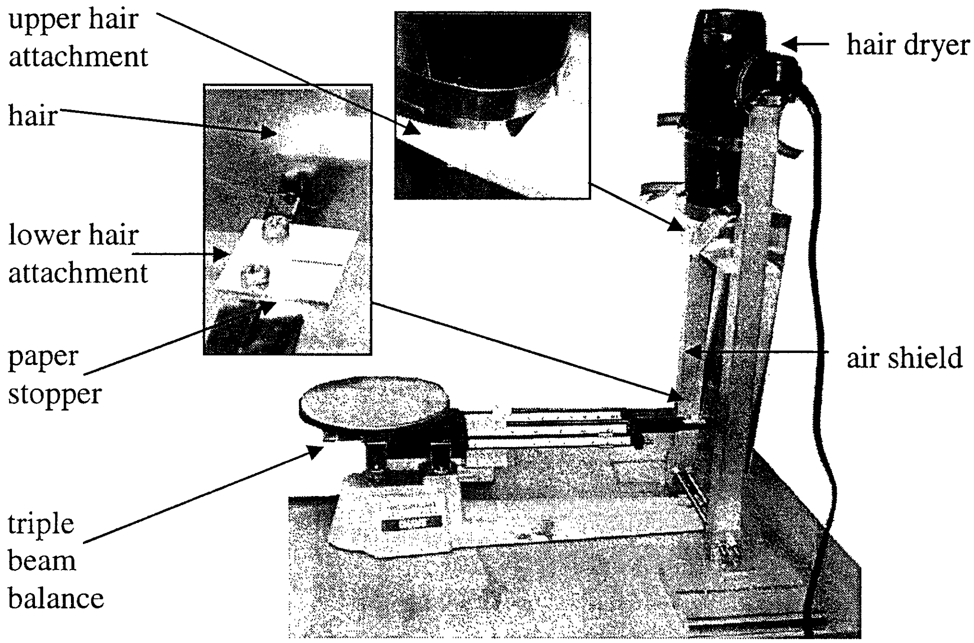

Figure 4: Setup of straightness vs. tension experiment

The hair dryer blew heat axially onto the hair so that it did not bend the hair in any unintended direction. The hair was positioned vertically between the hairdryer and the end of the balance. It was held in place by sliding it through two attachments (slits), labeled in figure 4. Each piece of hair tested had a small piece of paper glued to either end. The paper kept the hair from sliding through the slits. To change the tension on the hair, the weights on the balance were moved left or right.

The first part of this experiment was calibrating the balance. This consisted of placing weights on both the hair tip end and the traditional measuring end of the balance. This calibration was important not only because of the difference in moment arms but also because the end of the balance was changed from a pointer to a hair holding slit.

Next, the hair samples were prepared. Each end of each piece of hair was Krazy Glued™ to a small piece of white paper. Each of these pieces was then photographed.

The formats of these photographs were uniform. One end of the hair was placed on a mark and the hair was allowed to rest or its natural position. The hair was then rotated about the first end so that the second end came to rest on a specific line. The hair was still in its natural position.

Each piece of hair was put into the slits of the setup and brought to a specific tension. The hair dryer was then turned on for fifteen seconds. The hair was then removed and an after picture was taken in the same orientation as the before picture. Figure 5 shows a piece of hair before and after a force of 0.08N was applied. The rest of the before and after hair pictures are shown in appendix A.

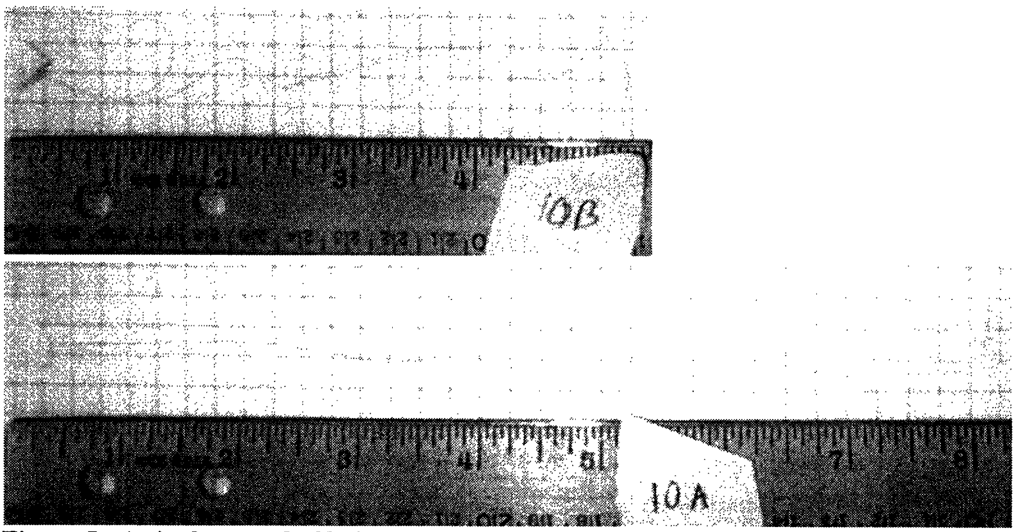

Figure 5: A single strand of hair. The top picture shows the hair before any heat or tension was applied to it. The bottom picture shows the same hair after heat from a blow dryer and a 0.08 N tensile force was applied to it.

In order to quantify the relationship between tension and change in straightness, it is first necessary to quantify change in straightness. For my purposes, it is acceptable to define change in straightness as the ratio of new unstretched length over old unstretched length. A curly hair is shorter than the same hair when it is straight. Figure 6 shows the relationship between tension and change in straightness.

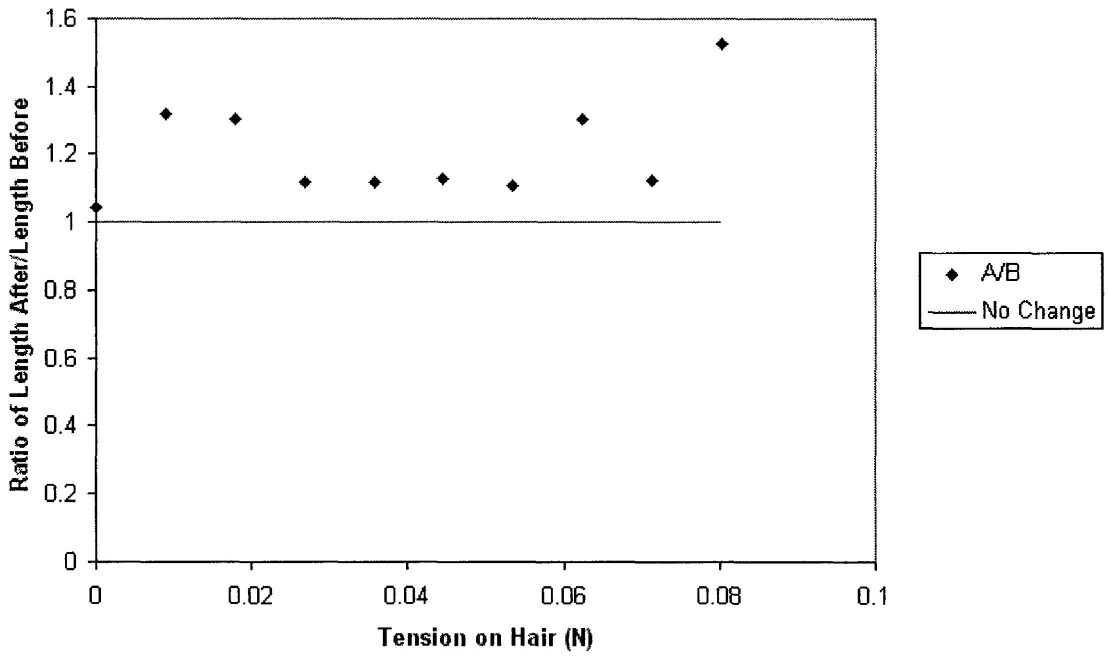

Figure 6: Change in straightness vs. tension in a single hair

The plot of change in straightness vs. tension shows no correlation between straightness and tension. However the one hair that did not have any tension on it only straightened slightly. That slight change could have been due to the slight amount of axial force provided by blowing the air along the hair axially. The hairs with tension and heat applied to them did straighten. Possibly, there is some minimum tension needed to break the hydrogen bonds which exists somewhere between 0 N and 0.0089 N, which was the smallest force applied to a hair in this experiment. Further work is needed to verify that.

3 Developing Strategies

The problem of hair straightening has been around a long time. Over the last 50 years countless devices have been created to solve this problem. Therefore in order develop strategies I must first look at all the existing strategies.

3.1 Existing Strategies

The most common existing hair straightening strategy is to heat the hair by conduction and then pull down on the hair to create tension. This is employed primarily by flat irons. A flat iron is two conductive surfaces hinged together which are compressed while hair is in between them and then pulled down the length of the hair. Figure 7 shows a CHI Turbo Ceramic Flat Iron. Figure 8 shows the physics of the flat iron.

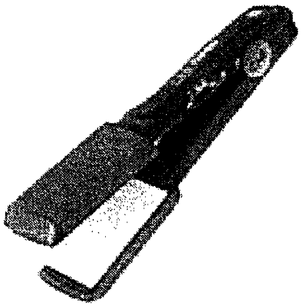

Figure 7: CHI Turbo Ceramic Flat Iron [5].

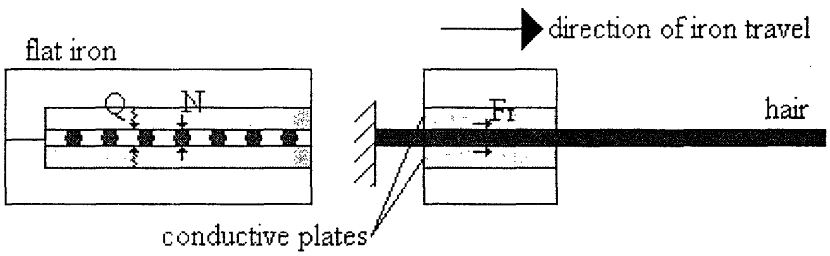

Figure 8: The physics of how a flat iron works.

The hair is compressed with a normal force N which causes a frictional force Fr when the flat iron is pulled in the direction shown in figure 8. Frictional force Fr results in the hair being in tension. Thermal energy Q is then transmitted to the hair through the conductive plates which causes the hair to heat. This type of device can only straighten a one thin layer of hair at a time. This makes straightening thick hair a very time consuming process.

Another very common existing strategy is to heat the hair by convection and pull on it to create tension. This is most commonly done with a blow dryer and a round brush. The hair is held taught over the round brush and the blow dryer is aimed down at it. The brush is then pulled along the length of the hair. Many variations of this concept also exist such as a blow dryer with bristles and a round brush which blows hot air. Figure 9 shows a typical blow dryer and several other related products. Figure 10 shows how a blow dryer is used. Using a traditional hair dryer and a brush works well but requires the user to use both arms which can be very tiring. Hair dryer brush hybrids, like those shown in the center and right of figure 9, often blow hair away from the device resulting in a frizzy finish.

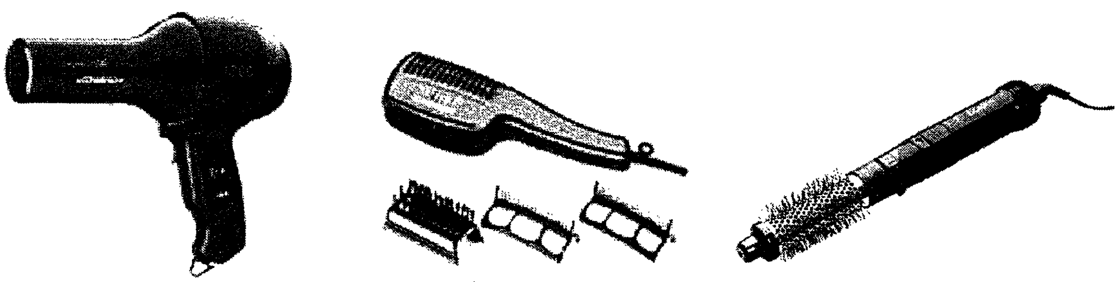

Figure 9: Variations of the hair dryer. Left- Conair Pro Avanti Professional Dryer [4]; Center- Hot Tools Brush Hair [5]; Dryer Right-Conair Hot Thermal Brush [4].

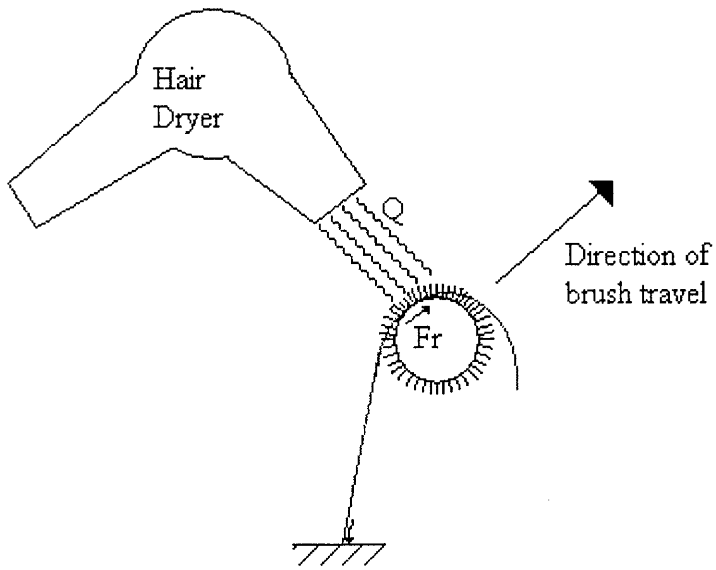

Figure 10: The physics of how a hair dryer works.

In this case shown in figure 10, the effective frictional force Fr is caused by the bristles essentially grabbing on to the hair as the brush travels in the direction shown. The exact way this works is a little more complicated. Thermal energy Q is transferred from the hair dryer to the hair by convection through hot air blowing out of the dryer.

A less common but more effective strategy is permanently, chemically straightening hair. This used to result in dry, brittle hair; however, new processes such as Japanese thermal reconditioning do not damage hair. Many salons now offer some type of this treatment. This process typically takes between 3 and 6 hours depending on the length of hair. It costs between 300 and 600 dollars per session and must be repeated every six months.

3.2 New Strategies

After considering conduction and convection as potential strategies, radiation is the next logical strategy since it is the third way to transfer heat. However radiation would most likely heat the head as well which probably would not be the most pleasant experience.

The *wet set* is a well known concept but not used in any commercial products. The idea behind it is that if hair is held in tension while it dries, the hydrogen bonds will break without a heat source. This is a healthy way to straighten hair because it does not over dry it. However, this type of set would require the hair to be kept in tension for several hours which is extremely impractical.

3.3 Choosing a Strategy

In order to choose a strategy I first made a list of functional requirements that the strategy would have to satisfy. These requirements were low cost, straighten hair in minimal time, easy to build, and safety. I chose low cost because I wanted to have a large customer base. I chose minimal time because I want my hair straight as fast as possible. I chose easy to build because I only have a short time to design and build a prototype. Safety was chosen for obvious reasons. I then compared the five potential strategies in a Pugh chart, shown in table 1.

Strategy	Low Cost	Quick Time	Easy to build	Safe	Total
Conduction	0	0	0	0	0
Convection	0	0	0	0	0
Chemical	---(very expensive if anything like current products)	++(only have to do it once every 6 months)	---(beyond my area of expertise)	0	-4
Radiation	0	-	0	- (possibly heat the person as well as the hair)	-2
Wet Set	+ (no heat supply)	--(would take several hours)	0	0	-2

Table 1: A Pugh chart comparing five possible strategies.

The Pugh chart shows that conduction and convection are the best strategies. To further compare them I experimented with both of them.

I wanted to get a feel for how well existing products worked. I let my hair dry naturally one day, straightened it with a flat iron another day, and straightened it with a hair dryer and brush on another day. The results can be seen in Figure 11.

Figure 11: Results of different types of hair straighteners. Left-drying naturally; Center-Flat Iron; Right-Hair Dryer and Round Brush.

Using the flat iron, it took me 45 minutes to straighten my hair. Using the hair dryer and brush took me 80 minutes to straighten my hair. The flat iron gave me better results. The look was smoother. To further compare these two strategies, I created a FRDPARRC chart shown in table 2.

Functional Requirements	Possible Design Parameters (Concept's FRs)	Analysis	References	Risk	Counter Measures
Heat hair with Conduction	1) A flat brush with heated bristles. 2) A round brush with heated bristles. 3) A series of plates that would penetrate the hair deeper than a traditional flat iron.	1&2) Tension comes from friction with the bristles. 3) Tension comes from normal force of the plates causing friction.	1&2) Traditional brushes. 3) Traditional flat irons.	1&2) Bristles might burn head. 3) Too many plates might create pinch points and pull hair.	1&2) Insulated bristle tips. 3) Pay careful attention to any possible pinch points and design to minimize them.
Heat hair with Convection	1) An improved round thermal brush that sucks air in so it does not blow the hair away. 2) Make a more efficient hair dryer by creating an attachment which would keep air from scattering. 3) Create a hair piece that keeps the hair in tension to be used in conjunction with a typical hair dryer.	1) BLE, fluid flow via pressure differences. 2) Fluid flow through nozzles. 3) Straightness vs. tension experiment.	1) 2.005 textbook. 2) 2.005 textbook. 3) Robbin's *Chemical and Physical Behavior of Human Hair*.	1) Hair could get stuck in brush. 2) Increased heat might damage hair. 3) Constant Tension could be painful.	1) Have variable sucking pressure. 2) Only use with low heat hair dryers. 3) Do a BLE to find pain threshold and design accordingly.

Table 2: FRDPARRC comparison of conduction and convection strategies.

After looking at the FRDPARRC table I decided on the conduction strategy. This was because the possible concepts were more innovative and interesting, the analysis was simpler, there were already proof of concept devices in existence, and the risks seemed more manageable.

4 Developing Concepts

After deciding on the strategy of using conduction to heat hair, a concept had to be chosen. The strategy FRDPARRC chart listed three possible concepts: a flat brush with heated bristles, a round brush with heated bristles, and a series of plates that would penetrate deep into the hair. All three of these concepts worked off the idea that increasing the surface area will decrease the amount of time needed to straighten all the hairs on someone's head. In order to choose one concept, some first order analysis was done on each and they were compared using both a Pugh chart and a FRDPARRC chart.

4.1 Explaining and Analyzing the Concepts

I developed the concept of a flat brush with heated bristles. It is an interesting concept because it might allow for straightening with just one hand and possibly straighten a greater volume of hair per stroke than a traditional flat iron. The axial force needed is provided by the effective friction between the bristles and the hair. Figure 12 shows how the flat brush with heated bristles compares to a traditional flat iron.

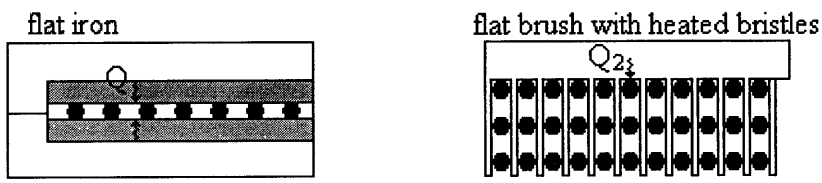

Figure 12: Comparison between a traditional flat iron's hair volume and a flat brush with heated bristles hair volume.

Looking at figure 12, it appears as though the flat brush with heated bristles could potentially straighten 5 times more hair per stroke then a traditional flat iron. This would mean that Q_2 would have to be 5 times greater than Q. Assuming that the Q is the heat needed for unit depth of the tool, that would mean each bristle (Assuming 11 bristles per unit depth as shown in figure 12) would have to emit 5/11Q in thermal energy.

The second concept is a round brush with heated bristles, which is very similar to the flat brush with heated bristles. The comparison in volume of hair straightened between this concept and a traditional flat iron is shown in figure 13.

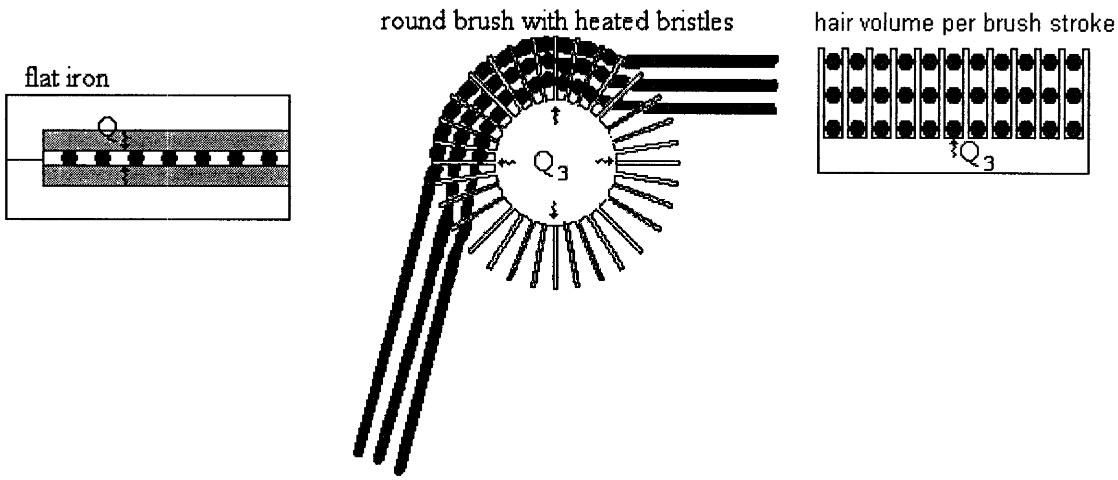

Figure 13: Comparison between a traditional flat iron's hair volume and a flat brush with heated bristles' hair volume.

Looking at figure 13, it appears as though the round brush with heated bristles could potentially straighten about 5 times as much hair as the flat iron. This would mean the 12 bristles in contact with the hair would have to conduct 5Q of thermal energy. Since the brush itself has 32 bristles, the total amount of thermal energy per width of the brush would be 5/12*32Q or 13.3Q.

The third concept would be a series of plates which would heat the hair through conduction. This concept could heat the same volume of hair as the flat brush with heated bristles. The axial force need to straighten hair would come from the friction between the plates and the hair. The difference between these two concepts is shown in figure 14.

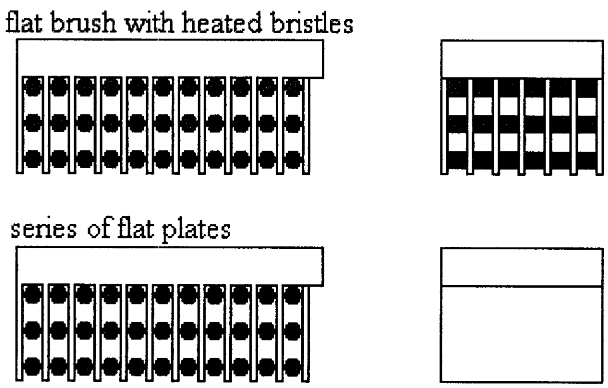

Figure 14: Two views of both the flat brush with heated bristles and the series of flat plates.

Since the series of flat plates concept is so similar to the flat brush with heated bristles, the physics of the flat brush with heated bristles applies. The series of flat plates can therefore straighten about five times as much hair as a traditional flat iron and requires five times the thermal energy. Since the plates would be rigid, it could be really hard to get them through the hair. If the device can not penetrate the hair, it can not straighten it.

4.2 Choosing a Concept

To better compare the concepts I rated them in a Pugh chart. The characteristics I chose to rate were efficiency, uniqueness, and easiness to build. Efficiency is defined as the volume of hair divided by the amount of thermal energy the design needs. Energy is in terms of Q, the energy needed for a traditional flat iron. Volume is in terms of V, the amount of hair that can be straightened by a traditional flat iron. This comparison is shown in table 3.

Concept	Efficiency	Uniqueness	Easy to Build	Total
Flat brush with heated bristles	0 (efficiency =5V/5Q)	0	0	0
Round brush with heated bristles	- (efficiency = 5V/13.3Q)	0	- (it is much easier to build things on a flat plane than a round plane)	-2
Series of flat plates	0 (efficiency =5V/5Q=1)	0	0	0

Table 3: Pugh chart of concepts

The Pugh showed that the flat brush with heated bristles and the series of flat plates were better concepts than the round brush with heated bristles. These two concepts were then further compared with a FRDPARRC chart, shown in table 4.

Functional Requirements	Possible Design Parameters (Modules's FRs)	Analysis	References	Risk	Counter Measures
Straighten hair with a conductive flat brush with heated bristles	1) Bristles that act like conducting fins. 2) Bristles with heating elements looped inside them. 3) Conducting bristles which are heated by internal convection (hot stationary air).	1) Thermal analysis of fins. 2) Thermal analysis of constant heat flux heating elements. 3) Thermal analysis of constant heat flux.	1) 2.005 text book. 2) 2.005 text book. 3) 2.005 text book.	1, 2, & 3) Bristles might burn head.	1, 2, & 3) Insulated bristle tips.
Straighten hair with a series of conductive flat plates	1) Straight, non moving plates. 2) Spring loaded plates for even more normal force. 3) Plates with strange topographies to optimize the straightening.	1) Thermal analysis of conductive plates. 2) Thermal analysis of conductive plates. 3) Thermal analysis of conductive plates.	1) Hot plates 2) Traditional flat irons. 3) Current atypical topography straighteners on the marker.	1) There will not be enough friction to create axial force. 2) Moving plates mean more pinch points. 3) Topography could be hard to manufacture.	1) Rough up the plates to increase friction. 2) Incorporate an anti pinch point mechanism into the hinges. 3) Could make flat plates if time runs out.

Table 4: FRPARRC comparison of concepts.

After looking at the FRDPARRC I decided on the flat brush with heated bristles strategy. This is because the possible modules seemed more exciting to me and the risks seemed more manageable.

5 Modules

The heated bristles were the most critical module for the brush with heated bristles concept. The concept FRDPARRC chart listed three possible modules: bristles that act like conducting fins, bristles with heating elements looped inside them, and conducting bristles which are heated by internal convection (hot stationary air). In order to choose one module, some first order analysis was done on each and they were compared using a Pugh chart.

5.1 Explaining and Analyzing the Modules

The first module I considered was having the bristle act as a fin heating element. The base of the bristle would be heated and the heat would be carried along the length of the bristle via conduction. In this case the base would be significantly hotter than the tip of the bristle. This could be manufactured by injection molding or using stock plastic rod. This module is shown in figure 15.

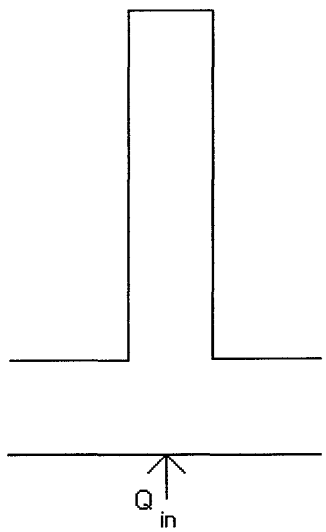

Figure 15: Bristle acting as a fin element. The bristle is solid plastic. The base is heated and conduction carries the heat through the bristle.

Next, I considered looping a heating element inside the bristle. This meant that power would be dissipated equally along the length of the bristle so that the tip of the bristle was the same temperature as the base of the bristle. This could be manufactured by injection molding the bristles around the heating element or by inserting the heating element into plastic tubes. This module is shown in figure 16.

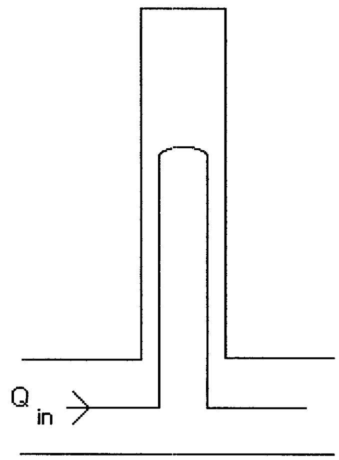

Figure 16: Bristle with a looped heating element through it. Current is run through the heating element which dissipates heat uniformly along its length. Therefore the bristle should be at a constant temperature along the length of the heating element.

Finally I considered having hollow bristles heated by heating the air inside them. This type of design would heat the bristle tip and base to approximately the same temperature. The brush would have to be sealed well. It would be difficult to injection mold hollow bristles. To manufacture this, the bristles could be injection molded and then drilled out or made of hollow tubes with end caps. This module is shown in figure 17.

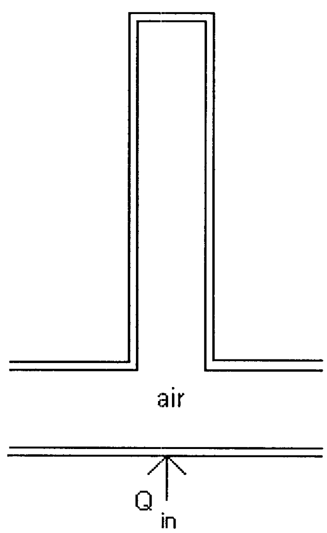

Figure 17: A bristle heated by convection. The bristle is hollow and the air inside it is heated. This air then heats the bristle.

5.2 Choosing a Module

To better compare the modules I rated them in a Pugh chart. The characteristics I chose to rate were manufacturability, consistency of heat throughout the entire device, and heat distribution along the bristle. Manufacturability was important due to time constraints. Consistency of heat throughout the entire device is important so that there are not hot spots. Heat distribution along the bristle is important because it determines the volume of hair that can be straightened per stroke. This comparison is shown in table 5.

Concept	Manufacturability	Consistency of heat throughout the device	Heat distribution along the bristle	Total
Bristles as a fin heating element	0	0 (solid materials often have defects and other things which could cause different heating throughout the brush)	0	0
Bristles containing a looped heating element	-(These are more difficult to make than a solid heating element)	++(using one continuous heating element should give very uniform characteristics throughout the device)	++ (A hot tip means much more hair is exposed to heat which leads to faster overall straightening)	+3
Conducting bristles heated by convection	--(These are more difficult that the looped heating element because they have to have a sealed end)	0(the air circulation might do strange things because of the shape of the brush resulting in hot spots)	++ (A hot tip means much more hair is exposed to heat which leads to faster overall straightening)	0

Table 5: Pugh of Modules

Since the Pugh chart favored the bristles containing looped heating elements so strongly, I decided to choose that as the bristle module.

6 Detailed Analyses

As discussed in the module section, it was decided that the bristles would each be hollow tubes containing the heating elements. The plastic used needed to be flexible so that it could be an effective brush and be able to operate at temperatures of 80 C to 90 C, the standard temperature for hair straighteners. The most readily available tubing that fit this description was nylon tubing. The dimensions of the bristles are labeled in figure 18.

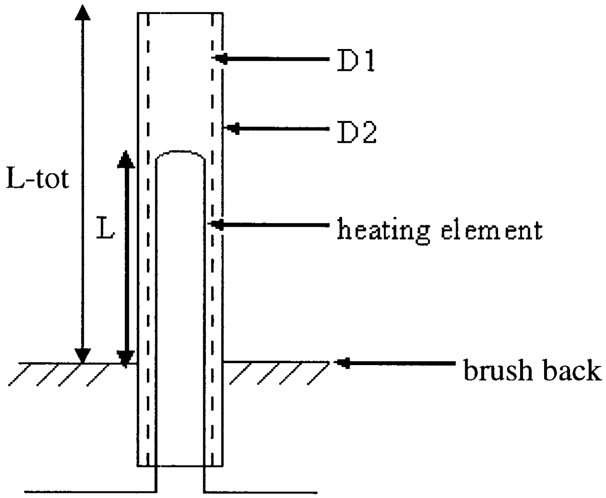

Figure 18: Schematic of a brush bristle. D1 is the inner diameter, D2 is the outer diameter, and L is the length of exposed bristle with heating element running through it.

The smallest available nylon tubing had an outer diameter of 0.125" and an inner diameter of 0.093". L was chosen to be 1" based on standard brush lengths. L-tot was chosen to be 1.5" so that the tip of the bristles would be cool enough to touch. The nylon had a maximum operating temperature of 82 C.

A thermal analysis was then performed to figure out how much power would be needed for the system to come to rest at 82 C. The system was modeled as a series of resistors as shown in Figure 19.

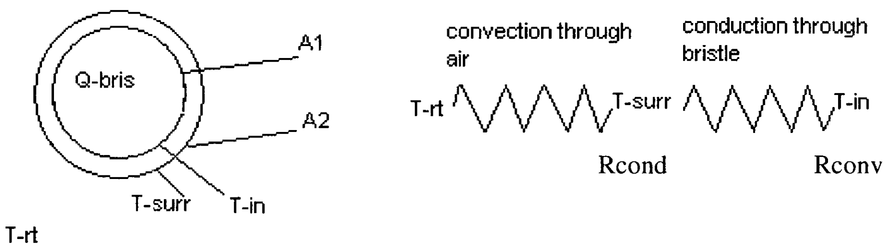

Figure 19: A schematic of the thermal resistances associated with the design. T-rt is the room temperature, T-surr is the temperature on the surface of the bristle, and T-in is the temperature on the inside of the bristle. Q-bris is the power dissipated in one bristle.

Many of the values in Figure 19 are known. The room temperature, T-rt, is approximately 21 C. The maximum T-in can be is 82 C. A1 and A2 are calculated below.

$$A1 = L * pi * D1 = 1 * pi * .292(in^2) = .292(in^2) = 1.88 * 10^{-4}(m^2) \quad \textit{(Eq 1)}$$

$$A2 = L * pi * D2 = 1 * pi * .393(in^2) = .393(in^2) = 2.53 * 10^{-4}(m^2) \quad \textit{(Eq 2)}$$

The equations for Rconv, the resistance from convection through air, and Rcond, the resistance of conduction through nylon, are shown below.

$$Rconv = \frac{1}{hA_2} = 790\left(\frac{K}{W}\right) \qquad (Eq\ 3)$$

$$Rcond = \frac{\ln(D_2 / D_1)}{2\pi kL} = 1.85\left(\frac{K}{W}\right) \qquad (Eq\ 4)$$

In the equations for Ronv and Rcond, h is the convection coefficient between nylon and still air and k is the coefficient of thermal conductivity of nylon. For this calculation h can be approximated as 5 $\frac{W}{m^2K}$ and k is known to be 0.3$\frac{W}{mK}$.

The relationship between the heat into the system per bristle Qbris and the total temperature difference is stated below.

$$Qbris = \frac{\Delta T}{\Sigma \text{Resistance}} = \frac{Tin - Trt}{\Sigma \text{Resistance}} = \frac{82 - 21}{790 + 1.85} = 0.0923(W) \qquad (Eq\ 5)$$

Since the design calls for 58 bristles, the total power need is

$$Qtot = 58 * Qbris = 5.35(W). \qquad (Eq\ 6)$$

The heating element proposed is Nickel Chromium wire having a diameter of 0.64 mm and a resistance per foot of 1.03Ω. Since each bristle will contain approximately 3 inches (0.25 ft) of wire and there are 58 bristles the total resistance of the heating element (Rwire) will be approximately 15Ω. Using this and the value of Qtot, voltage V and Current I can be found.

$$Qtot = VI = 5.35W \rightarrow V = 8.95V \qquad (Eq\ 7)$$

$$Rwire = \frac{V}{I} = 15\Omega \rightarrow I = 0.6A \qquad (Eq\ 8)$$

The general equation for temperature in terms of voltage is

$$\frac{V^2}{Rwire * N} = \frac{T - 21}{\Sigma \text{Resistance}} \rightarrow T = \frac{\Sigma \text{Resistance}\, V^2}{Rwire * N} + 21 \qquad (Eq\ 9)$$

where V is in volts, T is the temperature of the nylon bristle in degrees Celsius, and N is the number of bristles. ΣResistance is defined earlier as the sum of the resistances of the conduction through the nylon bristle and the convection through the still air.
Since these values can be obtained using a standard power supply, no extra electrical work needs to be done.

Since the thermal analysis worked out, construction of the prototype could begin.

7 Fabrication and Testing

I first attached the bristles to the base. I decided the best was to do this would be to press fit them. Since the diameter of the bristles was 1/8" I decided the thickness of the brush base needed to be at least 3/8" thick based on St. Venant's principle. Since I had 3/8" polycarbonate readily available and it had a high enough maximum operating temperature, I decided to use that.

I decided to make a test piece using the drill size one size below 1/8". Since the nylon was hollow and long, there was a high probability that it would buckle. To avoid this I created a press fit helper shown in figure 20. This helper consisted of aluminum block with a 1/8" blind hold which was just deep enough so that 3/8" of each bristle was sticking out. I was then able to press fit a bristle into the sample piece, shown in figure 21.

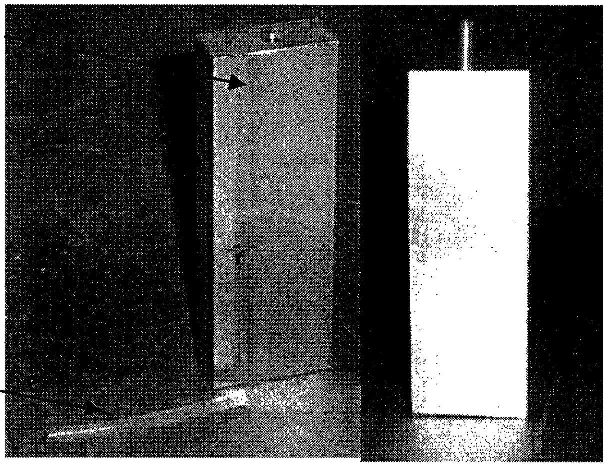

Figure 20: Right: One nylon bristle and the press fit helper, which prevented buckling during press fitting. Left: The bristle inside the press fit helper.

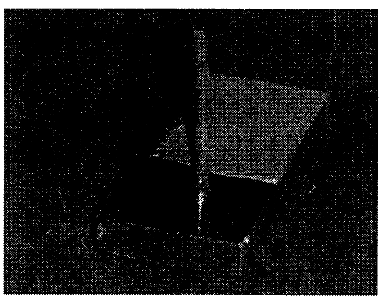

Figure 21: Sample press fit.

Next the lexan brush base had all 58 holes drilled and then all 58 bristles were press fitted into place. This result is shown in figure 22.

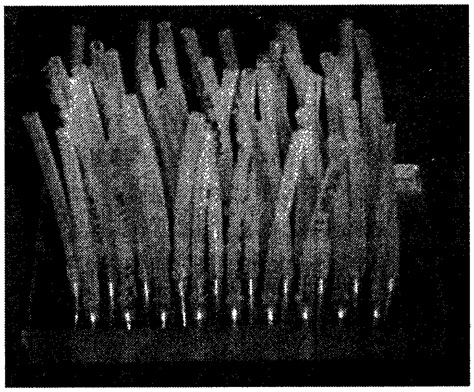

Figure 22: Bristles press fit into lexan brush back

I then tried to brush my hair with the partially built prototype to ensure that it could indeed brush hair before continuing with the fabrication. It did brush through the hair quite well without any pain. This is show in figure 23.

Figure 23: Testing the effectiveness of the brush head at brushing hair. It worked well.

Then I began to fold the Nickel Chromium wire into the appropriate shape to go into and out of each bristle. One thing I had not anticipated was the non insulated wire touching itself at the base and having the current not travel through the bristles. A diagram of this is shown in figure 24.

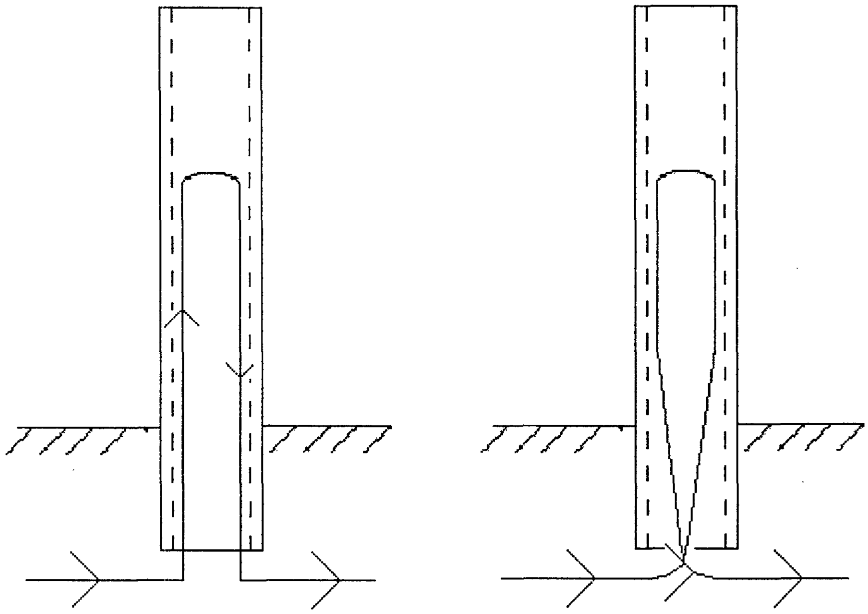

Figure 24: The path on the left gives the desired heat transfer effects. The current path on the right makes the heating element act as a fin as opposed to a constant heat flux.

In order to correct the behavior seen in figure 24, I decided to use insulated wire. However, no readily available insulated wire had the bend radius necessary to fit inside the bristles. However, Kapton tape, which is an insulating material rated at 500 F, was readily available. So I proceeded to make my own insulated wire with the Kapton tape. I first cut the wire to length (enough to make one whole row of bristles), then laid it flat on the table, and then wrapped it in Kapton tape as shown in figure 25.

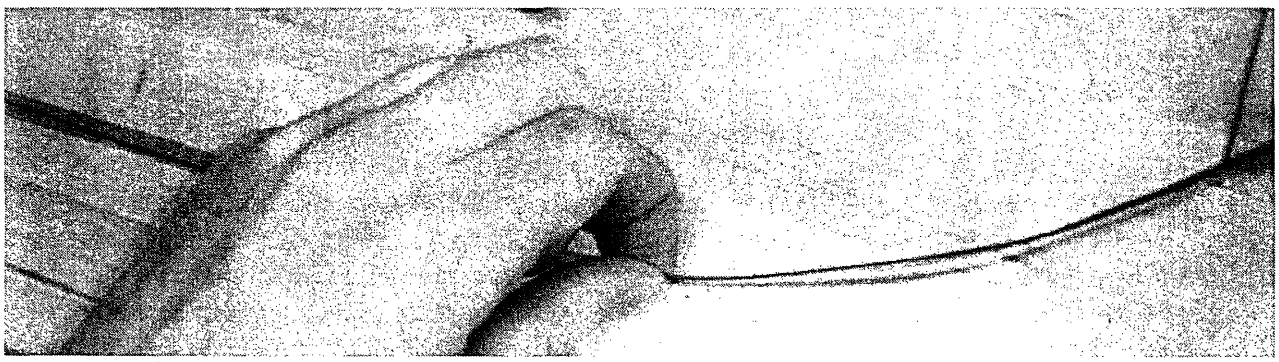

Figure 25: Nickel Chromium wire being covered in Kapton tape insulation.

Then I folded it along a printed diagram to get the wire into the correct shape to be inserted into the bristles, as shown in figure 26.

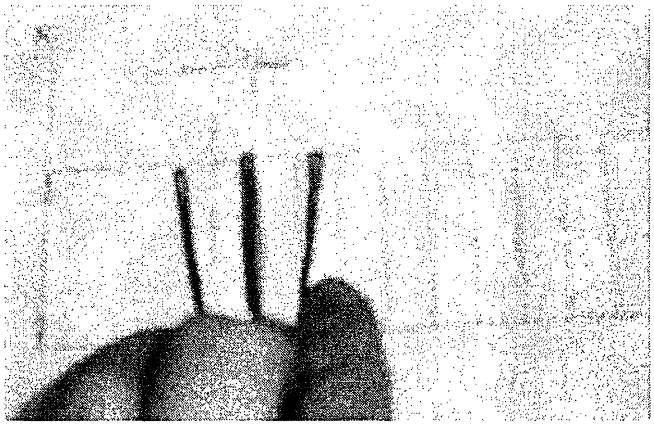
Figure 26: Nickel Chromium wire being folded into the correct shape.

I then did this five more times and then inserted all five rows into the brush back as shown in figure 7.8. I also went around the outside of the brush back with Kapton tape for added insulation.

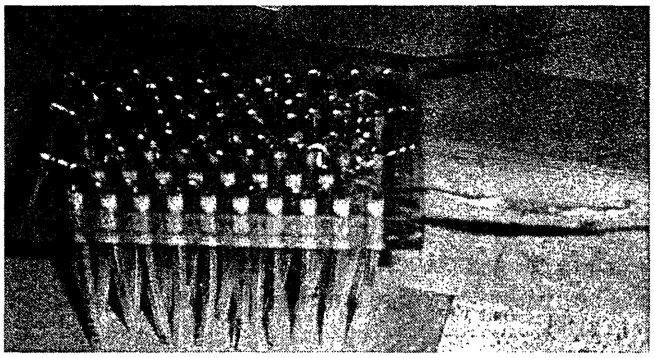
Figure 27: Kapton wrapped Nickel Chromium wire inserted into the bristles.

Since it is hard to predict how still air will transfer heat and because the Kapton tape had not been included in the earlier analysis, thermocouples were attached to the base of a bristle and the tip of a bristle to experimentally determine the relationship between voltage and temperature. The base of the bristle is defined as the area of the bristle closest to the base. Since the base and the bristles are heated, this would be where the nylon bristle would reach its maximum temperature. Since the nylon's maximum operating temperature is 82 C, I wanted to make sure the nylon never exceeded 80 C. Heat transfer analysis shows a negligible temperature difference between the inside of the nylon tube and the outside. Since the heating element stops half an inch before the end of the bristle, the very end of the bristle, also called the tip, should be significantly cooler. Since there is a risk that the tip might touch the user's head, the tip should be kept below 29 C. It should be noted that human hair is not damaged by temperatures below 90 C [2]. That is why thermocouples were placed on the base and tip. These locations are labeled in figure 28.

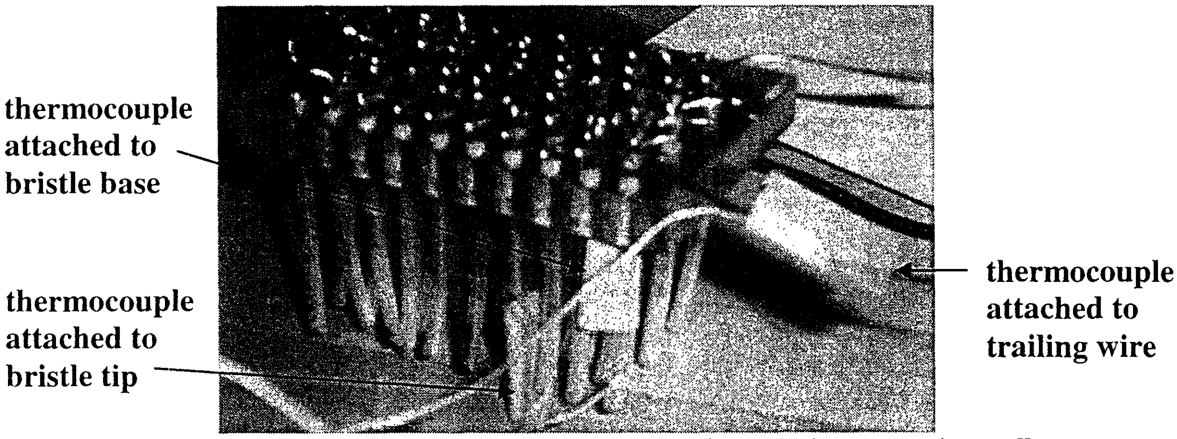

Figure 28: Thermocouples attached to the bristle base, bristle tip, and wire to experimentally determine the voltage the device could safely handle.

A power supply was attached to the Nickel Chromium wire. It was started at 4.07 V, 0.25 A and gradually increased until 22.5 V, 1.4 A. Every time the voltage was increased the system was allowed to come to equilibrium and the temperatures were all recorded. The measured resistance was 16.25 Ω, very close to the 15 Ω roughly predicted. Figure 29 shows the temperatures of the base and tip of the bristle as the voltage was increased. It also shows the values of temperature predicted by equation 9.

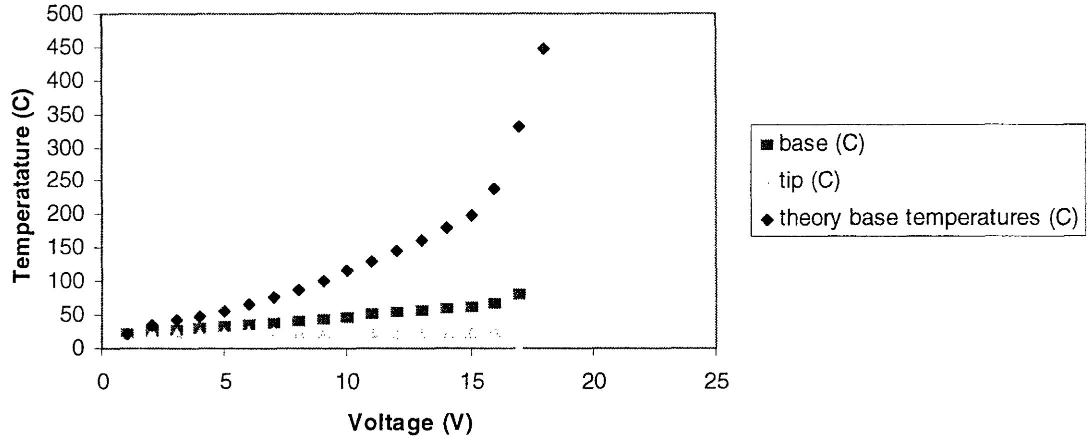

Figure 29: Theoretical temperature of the bristle base, temperature of a bristle tip, and temperature of the bristle base as the voltage through the brush was increased.

There are two reasons for the large discrepancy between the predicted values of base temperature and the actual base temperature. The first is that the Kapton tape was not included in the original heat transfer analysis. The second is that it is hard to predict the heat transfer characteristics of still air. Since the temperature reached 80 C, the maximum allowable temperature, at 1.4A, it was decided to run the device at 1.35A to be on the safe side. Also the maximum temperature the tips reached was 27 C, 2 degrees below the maximum allowable temperature. Therefore the tips should not burn the scalp. The exact data points are listed in Appendix B.

In order to test the brush on people, a handle had to be attached. Wood was chosen because it is a good insulator and therefore would stay cool. Figure 30 shows the brush with the handle attached.

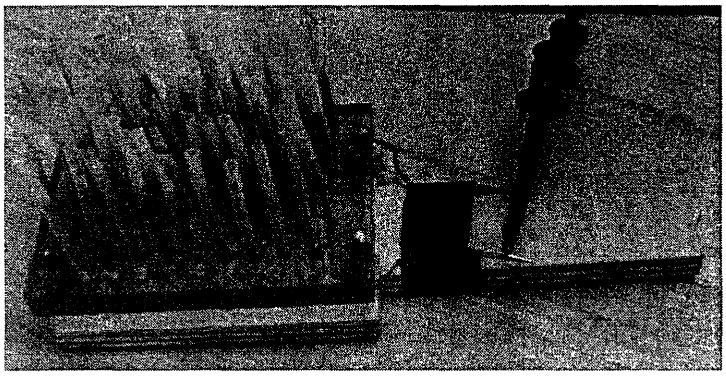

Figure 30: The finished prototype!

The last step before testing on people was doing one more thermal test to ensure that the product was safe. The brush was plugged into the power supply at 21.7 V, 1.35 A, and then the temperature at the base was recorded every minute. After about 12 minutes the brush started getting slightly hotter than was desired. At this point the power was lowered to 20.8 V, 1.3 A. This level of power held the temperature constant for an additional ten minutes. These results are shown in figure 31. The full set of data is shown in appendix C.

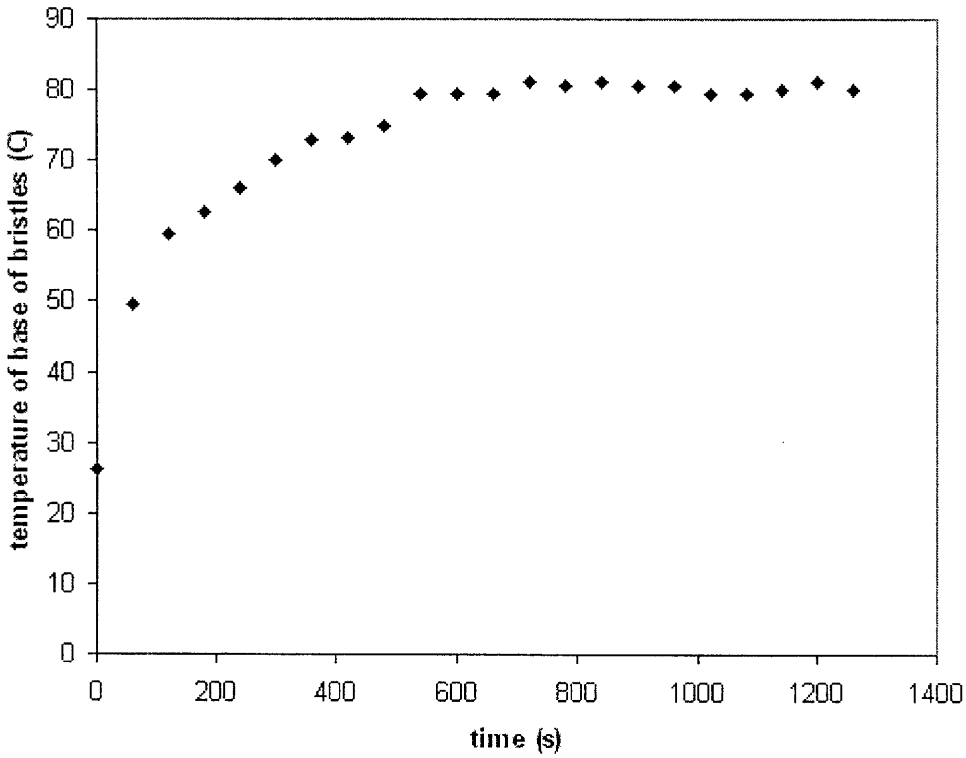

Figure 31: Temperature as a function of time when powering the brush with 20.8 V, 1.3 A.

After all the safety testing was complete, human testing could begin. I had tested the product on two subjects. Each subject's hair was completely dry and had no styling hair products in it. I took a before picture of each subject. I then brushed a section of their hair for ten minutes. I then took an after picture of that section. The results are shown in figure 32.

Figure 32: The left side shows the subjects before any use of the product, the right side shows the subjects after using the product on a section of their hair.

While the hair is significantly straighter, there is still room for improvement. The second iteration should have an optimized bristle configuration. It should also use a plastic with a higher maximum operating temperature so that the brush can be hotter. A third improvement would be putting in a temperature switch instead of relying on equilibrium for temperature control.

8 Acknowledgments

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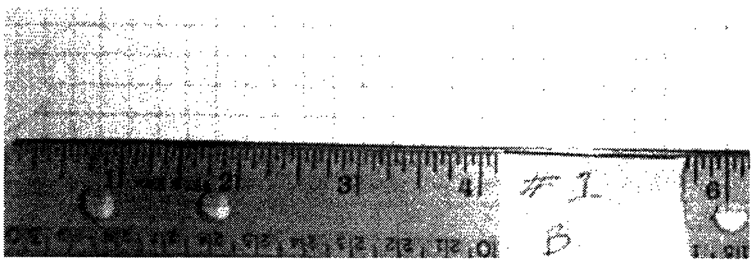
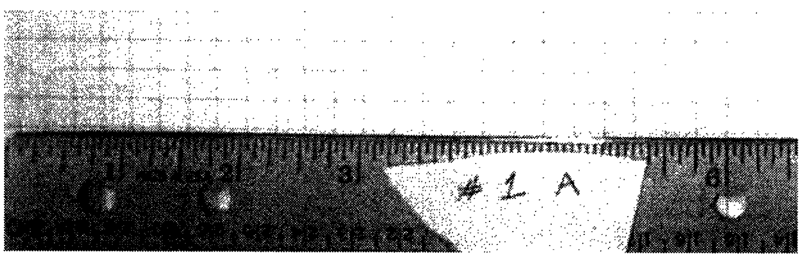
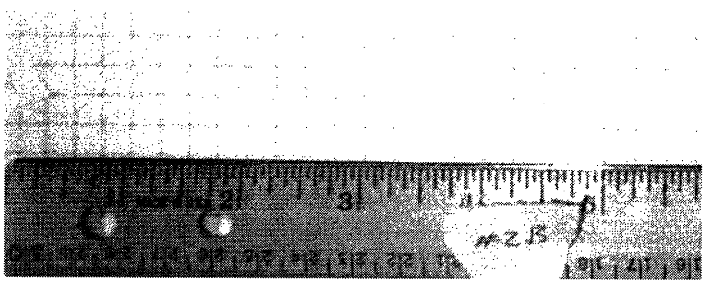
Appendix A

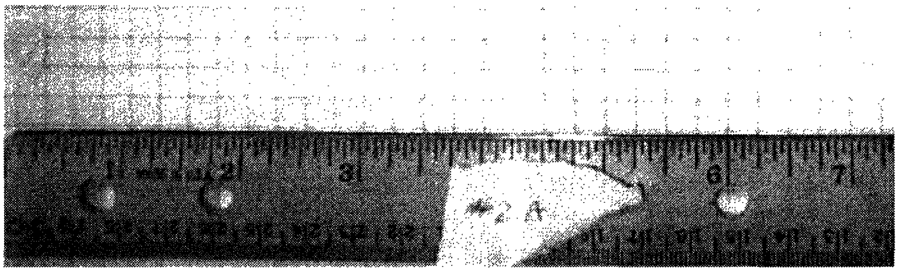
This appendix contains before and after pictures of hairs that were subjected to a certain tension. The 'B' denotes' before the experiment was performed and the 'A' denotes after the experiment was performed. The tensions applied to each hair are shown in table A.1

Hair Number	Tension (N)
1	0
2	0.008918
3	0.017836
4	0.026755
5	0.035673
6	0.044591
7	0.053509
8	0.062427
9	0.071345
10	0.080264





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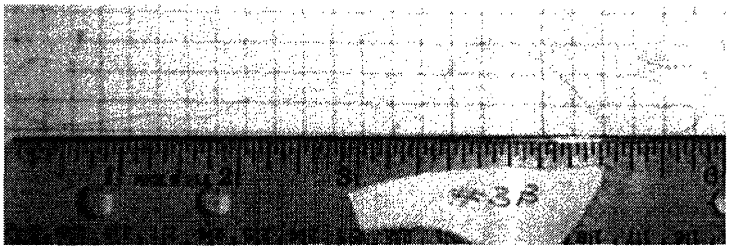
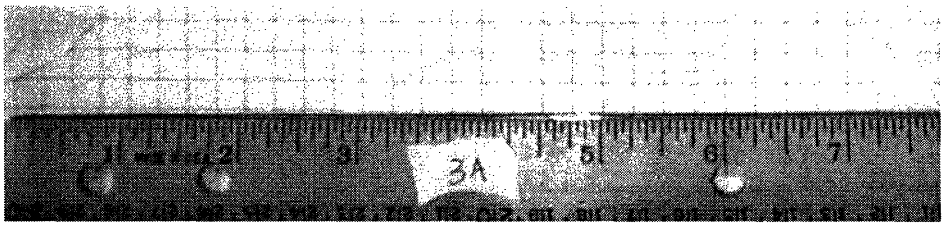

#3B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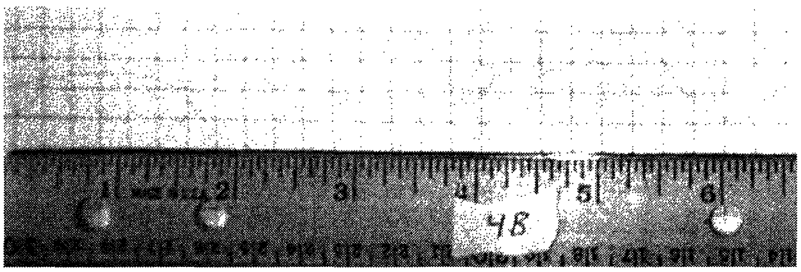
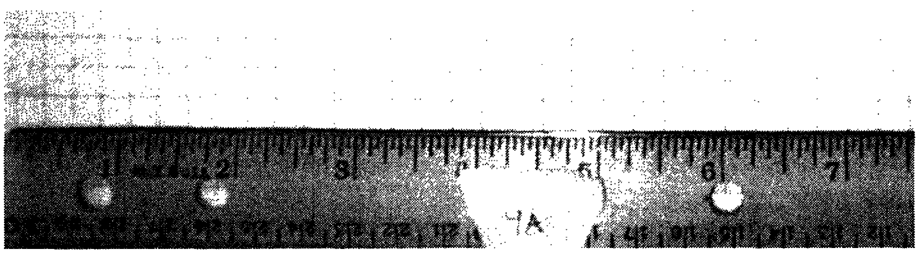

4B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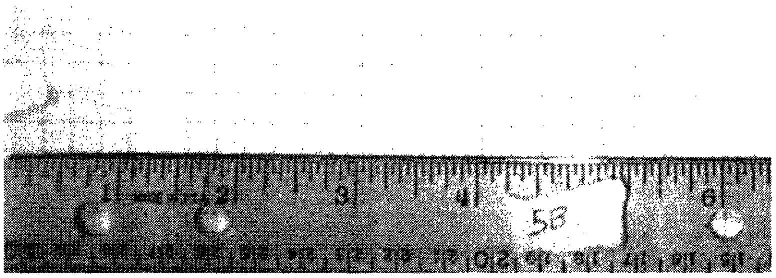
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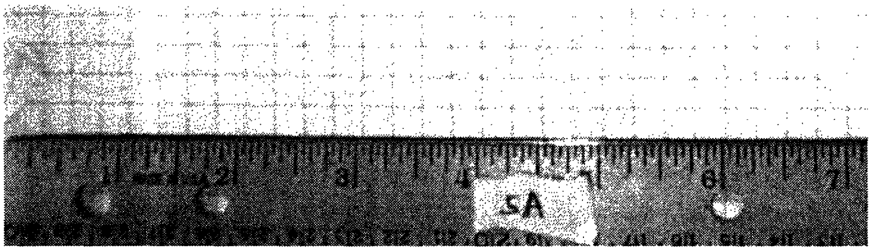
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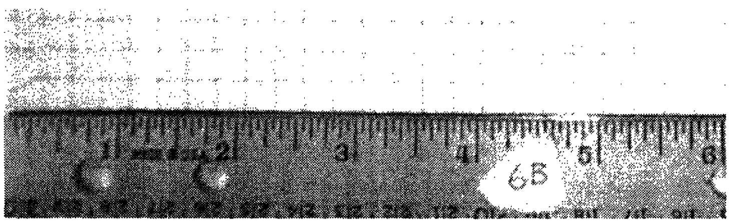
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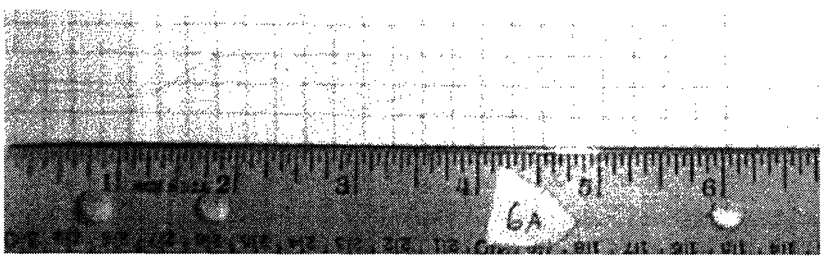
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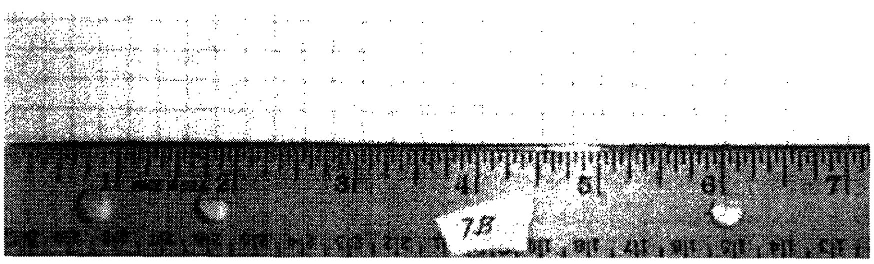
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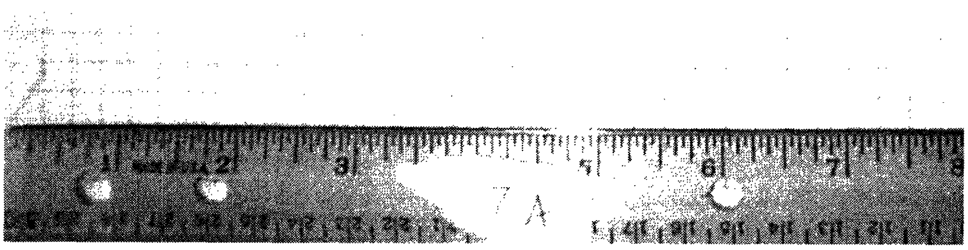
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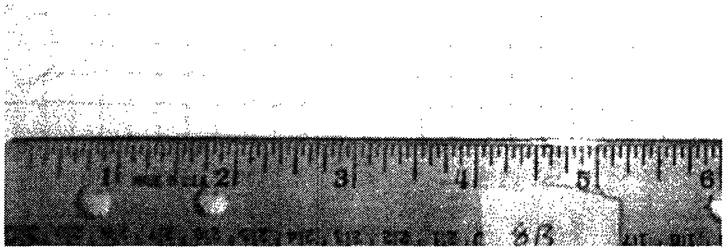
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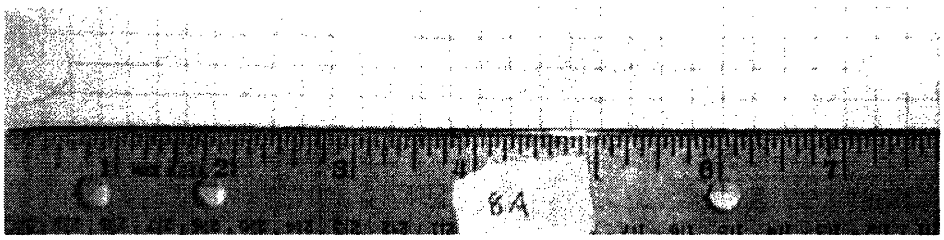
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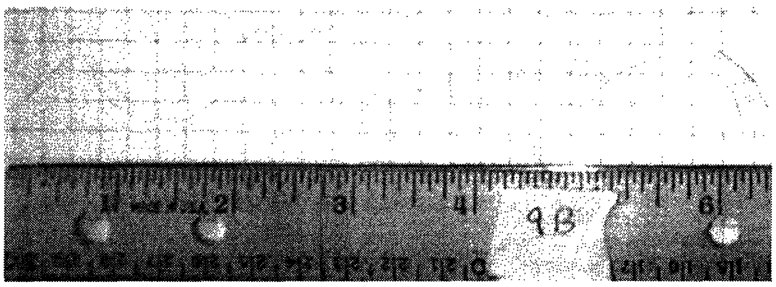
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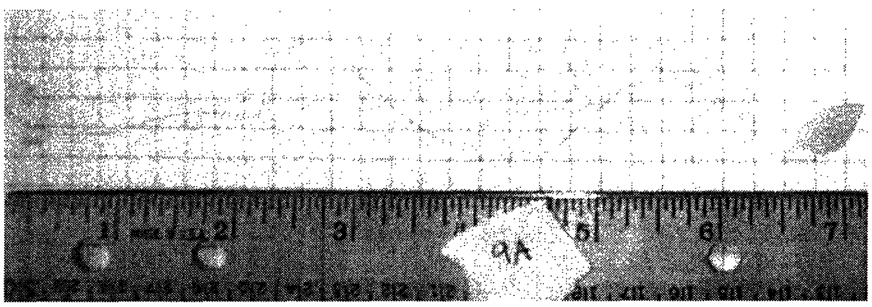
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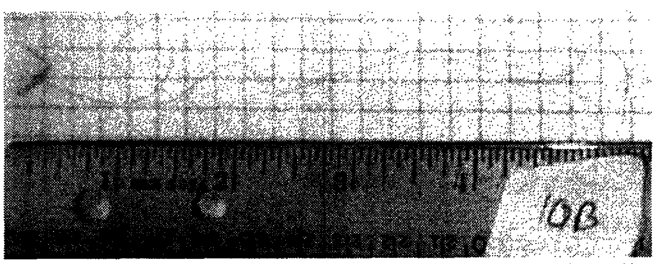
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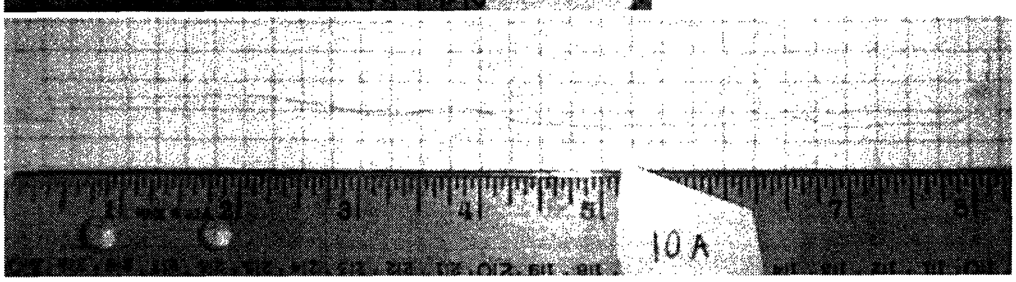
10A

Appendix B

It should be noted that the tip and wire thermocouples both popped off before the last measurement could be taken.

volatge (V)	amps (A)	base ©	tip ©	wire ©	base (F)	tip (F)	wire (F)	Power (W)
0	0	21	21	21	69.8	69.8	69.8	
4.07	0.25	22	21	22	71.6	69.8	71.6	1.0175
4.97	0.3	24	21	23	75.2	69.8	73.4	1.491
5.68	0.35	26	21	24	78.8	69.8	75.2	1.988
6.47	0.4	29	22	25	84.2	71.6	77	2.588
7.35	0.45	31	22	26	87.8	71.6	78.8	3.3075
8.12	0.5	34	23	27	93.2	73.4	80.6	4.06
8.89	0.55	37	23	28	98.6	73.4	82.4	4.8895
9.73	0.6	40	23	30	104	73.4	86	5.838
10.6	0.65	43	24	31	109.4	75.2	87.8	6.89
11.35	0.7	46	24	32	114.8	75.2	89.6	7.945
12.13	0.75	49	24	33	120.2	75.2	91.4	9.0975
12.95	0.8	52	24	34	125.6	75.2	93.2	10.36
13.75	0.85	55	25	36	131	77	96.8	11.6875
14.55	0.9	58	25	37	136.4	77	98.6	13.095
16.04	1	61	25	40	141.8	77	104	16.04
19.21	1.2	67	27	45	152.6	80.6	113	23.052
22.5	1.4	80	N/a	N/a	176	#VALUE!	#VALUE!	31.5

Appendix C

	time (s)	temp (F)
21.7V, 1.35 A	0	79
	60	121
	120	139
	180	145
	240	151
	300	158
	360	163
	420	164
	480	167
	540	175
	600	175
	660	175
	720	178
20.8 V,1.3 A	780	177
	840	178
	900	177
	960	177
	1020	175
	1080	175
	1140	176
	1200	178
	1260	176