WAPI (Memory Alloy Metal)

Final Report

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The Ohio State University

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(I've added a few editorial comments. Dale Andreatta)

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PROBLEM STATEMENT

This quarter, the five members of our group: Matt Garda, Josh Moran, Nathanael Young, Dan Bentley, and Gabe Stansberry, elected to complete the WAPI project specified by Professor Denny Guenther and Adjunct Professor Dale Andreatta. Our specific task involved building and testing WAPI (Water Pasteurization Indicators). The main driving factor for this project was, that upwards of 3.575 million deaths occur each year due to unclean drinking water, and most of those deaths are children. One way to kill off most pathogens in water is to heat the water to 65°C for approximately 1 minute. This temperature is known as the pasteurization temperature and the WAPI has been developed to determine when this temperature has been reached.

The specific type of WAPI being tested was a shape memory alloy wire indicator. A memory metal called Nitinol (Nickel-Titanium) has been designed with a temperature transition threshold of 65°C. The particular wire used for this application has one memory shape, which was straight for ease of manufacturing. The wire was bent into a U or S-shape when at a temperature below the transition threshold. When the wire reached the transition temperature it straightened itself out to the memory shape. Using a memory alloy for use as a WAPI is a relatively new idea, so our group needed to do some extensive testing to determine if the metal would be a good replacement for older methods. Many aspects of this particular WAPI design were tested including: thermal cycling, basic abuse, corrosion, and determining straightness as a function of temperature.

The major advantage of using a WAPI instead of simply boiling water is that the amount of energy needed to pasteurize water is significantly less than that needed for boiling. This is particularly important in a developing country where the main energy sources are limited to solar and biomass. Also, because these devices are used in developing nations cost becomes very important. For example, if a WAPI were to cost fifty cents and could only be used one time, the device would not be cost effective, but if the WAPI could be used multiple times then it becomes viable.

The WAPI had to be a very simple and intuitive product as to ensure that it can be used correctly and does not require extensive user training, which also helped to keep cost low. The memory alloy needed to noticeably change shape at or above 65°C, assuring that the pasteurization temperature had been obtained throughout the entire vessel. It was very important that even after several hundred uses, the wire would still deform enough to display a clear indication of whether or not the correct temperature had been reached. The amount of bend in the wire and size of the WAPI also had to be taken into account, since the containers used for water pasteurization range in opening and overall size. The WAPI had to be compact enough to fit through the mouth of a beverage bottle and at the same time be able to reach a depth of 18 inches. The following report encloses all the information needed to conclude that the memory wire WAPI is a safe, reliable, easy to use, long-lasting and cost effective alternative to previously developed WAPI types.

INTRODUCTION

According to water.org, every year roughly 3.58 million people die from water related illnesses, and 84% of them are children from ages 0 to 14. The lack of access to clean drinking water is a serious problem that needs to be addressed. There are many simple solutions that can help people obtain safe drinking water. Our team believes that the use of the wire WAPI will help people realize safe drinking water, therefore reducing the number of deaths associated with unclean water.

In 1992, Fred Barrett and Dale Andreatta invented the first Water Pasteurization Indicator (WAPI hereafter in this document). The need for the WAPI came about when people started understanding that, from a microbiology perspective, water does not need to be taken to a boil to be pasteurized. This fact is particularly important in developing nations where energy resources are limited, because the energy required for boiling is much greater than what is needed for pasteurization.

Figure 1: African Locals Learning About the WAPI

The common misconception is that for water to be properly pasteurized, its temperature must be increased to the boiling point. This misconception comes about because when water boils there is a clear indication that people can see. According to a paper in the journal titled, *Applied and Environmental Microbiology (Vol. 47:223-228, 1984)*, "all pathogenic microbes are inactivated when water is heated to 65°C (149°F)," where this is known as the pasteurization temperature (wikia.com). The main problem deriving from this fact is there is no natural phenomenon for people to sense that water has reached 65°C. Thermometers are too fragile and expensive for people in developing nations, so a better solution was needed for an indicator. This is why the WAPI is such a valuable tool in the pasteurization process, because it clearly indicates when water has reached 65°C.

The first WAPI developed was made with solid wax inside a clear plastic tube. The concept was, when the water would reach 65°C, the wax would melt and the user would have a visual indication the water was properly pasteurized. The downsides of this WAPI were that it could be broken quite easily, and if subjected to too high of a temperature the WAPI would be destroyed. The wire WAPI, on the other hand, is much more rugged. We feel that after extensive testing the wire WAPI will prove to be a much more viable option for the pasteurization application.

The wire WAPI will benefit people around the world who do not have access to potable water. Our main focus group is the impoverished people in both urban and rural areas who either cannot afford clean water or do not have access to clean water. According to *water.org*, "About a third of people without access to an improved water source live on less than $1 a day, and more than two thirds of people without an improved water source live on less than $2 a day." One goal of the team is to make the wire WAPI a one-time purchase for these people so they can have a water pasteurization indicator for the rest of their lives.

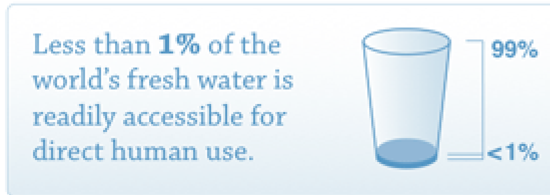

Figure 2: Amount of Consumable Water (water.org)

Up to this point, very little that has been done with the wire WAPI in regards to testing and publication. This project should be undertaken for this very reason. It was imperative to determine how this material behaved when subjected to a variety of conditions. Through testing the team observed whether the WAPI continued to indicate at the proper pasteurization temperature after many cycles and abuse. The WAPI has major safety implications if it was to stop working properly, and this project was a great way to ensure every user's safety.

THEORY

It was once believed that water needed to be boiled in order for all microbes to be destroyed. This was convenient because a person could see that water was boiling and knew that it had at least reached 100^{o}C. With the advent of greater techniques for detecting microbes in water, people discovered that water did not need to be brought to a boil in order for it to be safe for consumption. According to thorough research completed in a study of water pasteurization, the temperature required to kill all pathogens in water was 65^{o}C. This knowledge brought about the need for a simple and inexpensive device to indicate when water had reached 65^{o}C. The WAPI provided just the solution to this problem. The WAPI allows for pasteurization temperature, which is lower than the boiling temperature, to be distinguished. The water temperature must only be held at 65^{o}C for at least one minute in order for 99.999% microbes to be rendered inactive. For this reason it is unnecessary to bring water to a boil to ensure that it is safe for consumption. Tables 1 and 2 below, display the data to support these claims.

Table 1: Temperature Required to Kill Harmful Pathogens Found in Water.

Temperature [°C] Required to Kill 90% of Microbes within 1 Minute	Microbe Killed
55	Guardia, Cryptosporidium, Entamoeba
60	Vibrio Cholerae, Samonella Typhi, Shigella Sp, Enerotoxigenic Escherichia Coli
65	Hepatitis A virus

Table 2: What Percentage of Microbes are Inactivated at Different Durations of Time.

% Inactivation of Microbes	Time Required at 65 °C
90	12 seconds
99.999	60 seconds

Another reason why it is much more advantageous to bring water to pasteurization temperature as opposed to boiling temperature is energy conservation. As can be seen in Table 3 below, the energy required to pasteurize water is much less than the energy required to bring water to the boiling temperature. The equation used to determine the energies required, is listed below. The values for specific heat and mass of water used were, c= 4.186 J/g-°C and m=1000 grams, respectively. The ΔT term was equal to final temperature minus initial temperature. The initial temperature used for the calculations was 23°C.

$$Q = c * m * \Delta T$$

Table 3: Energy Required for Water Pasteurization vs. Boiling Water

Water Temperature [°C]	Energy Required [kJ]
65	176

100	322

Previous WAPI Designs

The initial design of the WAPI was comprised of a polycarbonate tube that was filled with a solid wax, which was used as visual indicator. With the wax located inside the tube, the ends of the tube were heated and pinched closed. When the tube was pinched closed, fishing line was strung through each end and metal washers were placed at either end of the fishing line. The washers were placed on the tube to ensure the WAPI would stay low in a water vessel, allowing for complete pasteurization indication. The process of making this particular design was a slow and sometimes difficult process to perform; therefore advancements were made to the design to speed up the manufacturing process.

One motion for progress on this particular design was made by implementing a new way to seal the ends of the tube. The alteration replaced the original method, where the ends where heated and pinched together, by adding tight fitting plugs to the ends of the tube. The plugs had pre-drilled holes for the fishing line and were hammered into place to ensure the wax was sealed inside.

A few years later a new prototype was developed at the Ohio State University under the direction of Professor Denny Guenther. This particular design implemented a spring and rod system to hold a wax filled capsule upright and near the bottom of a water filled container. The spring was made out of stainless steel, for corrosion resistance, and comprised of approximately 13 coils. The inner diameter of the spring was slightly smaller than the outer diameter of the capsule itself. The seven middle coils were used to wrap around the capsule. Additionally, three coils on either end of the spring were bent so that they were held perpendicular to the capsule, and a stainless steel rod could be tightly inserted through the coils. The coils allowed the capsule to be easily slid up or down the rod for any height adjustments that may have been needed.

Memory Alloy Metal WAPI

The wire WAPI utilizes a shape memory alloy that reverts to a predetermined unbent state when heated. This phenomenon occurs because of the atomic structure formed between the two metals that form the alloy. Figure 3 below, shows that the Martensite structure is deformed when stress is applied; in this case stress is applied to the WAPI wire when bent into a U or S-shape. When heated, the crystal lattice structure of the material changes from a Martensite to an Austenite form. As the material is heated and becomes a cubic structure it returns to the memory state shape, because in the Austenitic form, the original atom positions are always maintained. As the material cools it once again becomes Martensitic, which allows for the metal to again be bent, and the process repeated.

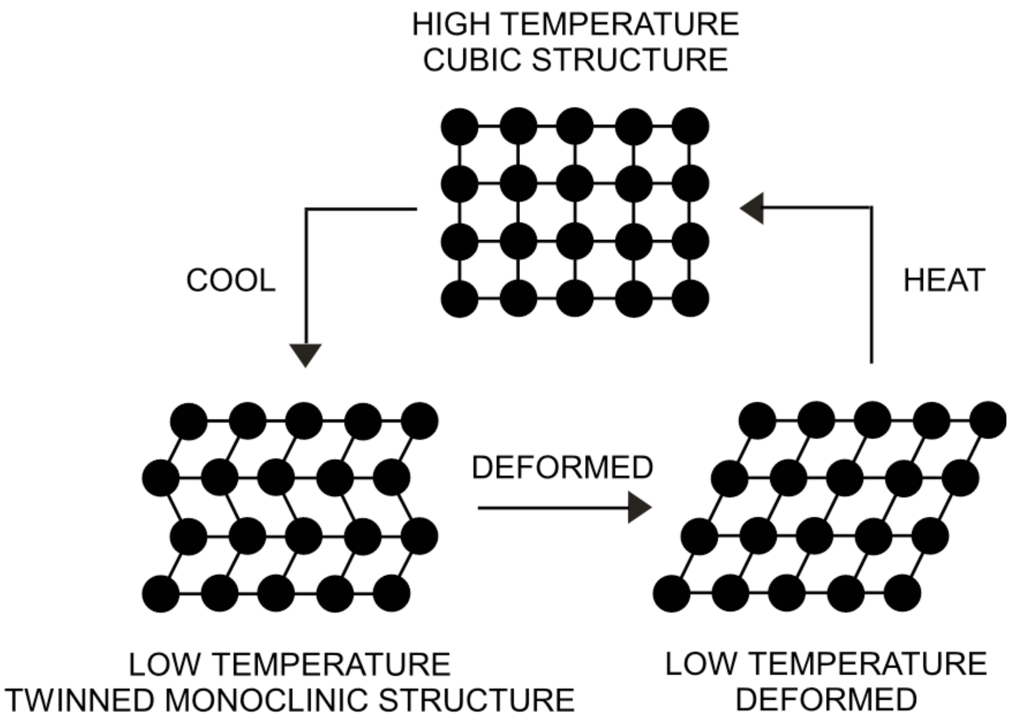

Figure 3: Deformed Memory Structure Recovery Cycle (Dapino)

The wire used in the WAPI application was nitinol which was a Nickel-Titanium alloy. This material could consistently recover from strains up to 10%. The stress needed to deform the wire at a low temperature was relatively low as the atoms were simply being realigned from the "twinned monoclinic structure" shown above to the deformed shape. As long as the wire does not experience amounts of strain large enough to damage the bonds between the atoms, no structural damage occurs and the memory shape can consistently be recovered. The transition temperature at which the wire reverts back to its memory shape is determined by relative amounts of Nickel and Titanium in the material.

CONSTRAINTS OF WIRE WAPI DESIGN

There were many constraints that the wire WAPI needed to meet, to be considered as a viable option for replacement of the current design. The wire WAPI needed to have the ability to be used in both flame and solar heating applications. The WAPI also had to be capable of being inserted and removed from a vessel with a narrow opening such as a beverage bottle as well as reach depths up to 18 inches. The overall cost of the wire WAPI was to be kept as low as possible because of their use in developing nations and non-profits are the main providers. The WAPI could not impart any adverse taste to the water being pasteurized. The transition temperature of the WAPI needed to be slightly above pasteurization temperature, but not too high that an excess of energy would be needed for indication of pasteurization. The design of the wire WAPI was to be simple with clear indication of successfully reaching the transition/pasteurization temperature.

RISKS

There was one significant risk involved with the WAPI project, which would pose extreme health risks for the end user. If the WAPI were inaccurate for any reason and indicated that that water had successfully been pasteurized, when in fact the water had never reached the proper temperature, severe illness or death was possible. For this reason the utmost care was given while performing the tests necessary to ensure this threat would not be realized. Consumer safety was always the number one priority and through the methods and tests discussed in this document the team worked to minimize the risk and maximize the overall safety of the final product.

EXPERIMENTAL METHODOLOGY

Experiments were performed to test as many aspects of the memory alloy metal wire, to ensure all constraints were met and risks were eliminated, for the pasteurization application. Testing was centered on making certain the transition temperature, and therefore the indication of achieving pasteurization, did not change over the life of a memory wire WAPI, regardless of imposed abuse. Most experiments were performed at 201 E. 19th Ave, Scott Lab at The Ohio State University, with a couple occurring at a group member's residence for convenience. All necessary equipment for testing was found at Scott Lab or provided by the members of the group.

PROPOSED TESTING

(What follows is a detailed description of the testing that was intended to be done. As it turned out, only a couple test samples were available, but most of the intended testing was done. DA)

High Cycle Testing

Purpose: Determine if the transition temperature changes over the life of the WAPI.

Test: Run the following for 5 or 6 separate WAPI. For 2000 cycles, bend the wire; place it in boiling water, move to cold water, and repeat. Check the transition temperature before and after the 2000 cycles to check the transition temperature's consistency.

Supplies Needed: 5 or 6 WAPI, 3 Hot Plates, 6 beakers, 1 thermometer.

Procedure:

1) Slowly heat hot water beaker with WAPI suspended in water. Determine the transition temperature in ºC before running the remainder of the experiment.

2) Remove WAPI from hot water, place in cold water beaker.

3) Continue heating hot water until boiling.

4) Bend memory wire (U-shape or S-shape), place in boiling water. After transition, pull out and place in cool water.

5) Repeat step 4, 1999 more times, adding water to boiling beaker as needed.

6) Repeat step 1 after completion of step 5.

Checking Straightness of Wire

Purpose: To determine if a false indication could be achieved over the life of a memory alloy wire WAPI.

Test: While cycling the WAPI in the High Cycle Test, every 200 cycles test the straightness of the WAPI as a function of temperature.

Supplies Needed: 5 or 6 WAPI, 3 Hot Plates, 6 Beakers, 1 Thermometer, 3 Dial Calipers.

Procedure:

1) Bend WAPI (U-Shape or S-Shape) and measure the wire from tip-to-tip.

2) Place beaker with water at room temperature on hot plate, suspend thermometer and WAPI in water.

3) Increase temperature of water slowly so that measurements can be acquired. Every 10ºC remove WAPI and measure tip-to-tip length, then replace WAPI in water.

4) As the water temperature nears WAPI transition temperature, begin taking measurements in 2ºC increments until the WAPI straightness is unchanged.

5) Repeat 3 times, then pick-up step 4 of High Cycle Test.

6) Repeat Steps 1-5 of this test every 200 cycles of the High Cycle Test.

Maximum Temperature Test

Purpose: If WAPI were to be introduced to extremely hot temperatures for any reason, would the transition temperature of the wire be compromised?

Test: Heat memory wire to around 400ºF, then test transition temperature.

Supplies Needed: Oven, 1 memory wire w/ 65-70 degree transition, 1 hot plate, 1 beaker, 1 thermometer

Procedure:

1) Set oven to 400^{o}F.

2) Place WAPI on a baking sheet and place in the oven.

3) After the oven has reached 400^{o}F, let the WAPI sit for 5 minutes, then remove for testing.

4) Bend WAPI and place in cool water.

5) Measure the length of the wire from tip to tip.

6) Slowly heat the water with the hot plate by small temperature intervals. Decrease the interval length after 56 degrees is reached.

7) Repeat step 6 until 72^{o}C is reached.

Abuse Testing

Purpose: To ensure that this type of WAPI cannot be easily damaged by "normal" every day usage.

Test: Determine if WAPI were to be caught on something, how much force would be required to break any aspect of the design.

Supplies Needed: 1 WAPI with stainless steel wire attached, 1 Set of weights with mounting stand, 1 pair of vice-grips.

Procedure:

1) Place end of WAPI, not attached to stainless steel wire, in the vice-grips.
2) Connect stainless steel wire to weight stand.
3) Add weight to stand until some aspect of the WAPI breaks.
4) Record which aspect failed and at what force this occurred.

Taste Test

Purpose: To ensure that the wire WAPI does not impart any adverse taste to the water.

Test: Place a WAPI in heated water for a few hours (multiple time increments would be preferred: 2, 4, 6 and 8 hours as four separate tests), preferably in a glass bottle. Heat another bottle for the same period without a WAPI inside. Using multiple people perform a double-blind test to determine if the WAPI water tastes different than the non-WAPI water.

Supplies Needed: 2 glass bottles per WAPI, 1 hot plate, 4 Styrofoam cups, 1 timer.

Procedure:

1) Fill 2 glass bottles with water and place them on the hot plate (group member 1).
2) Suspend WAPI in one bottle and turn on the hot plate.
3) Heat the water in the bottles for 2 hours.

4) After 2 hours, let the water cool.

5) When water is cool, remove WAPI.

6) Take bottles to a group member (2) who has no knowledge of which bottle has had a WAPI in it.

7) Second group member pours water from bottle A into two cups and water from bottle B into two cups. The cups will be correspondingly marked A or B.

8) Two other group members (3, 4) will then be asked from member 2 to each drink from a cup marked A and a cup marked B to decide if the two taste different from one another.

9) Group member 2 reports results to group member 1 who keeps the results a secret until the end of testing.

10) Repeat steps 1-9 for time intervals of 4, 6, 8 and 10 hours.

Corrosion Test

Purpose: To ensure that the wire WAPI does not significantly corrode over its life.

Test: Place a WAPI in a glass bottle for 1 month, preferably heated, and determine if any aspect of the WAPI has corroded.

Supplies Needed: 2 Assembled WAPI, 2 dark glass bottles, black paint (optional), 1 dial caliper.

Procedure:

1) Fill glass bottles with water (one with tap water, one with Olentangy river water)

2) Measure the diameter of WAPI wire with calipers and record.

3) Place the WAPI in the bottle.

4) Either a) place bottle near external heat source or b) place in a sunny area.

5) After about a month, remove WAPI from jar or bottle and repeat steps 2 and 3.

Static Temperature Test

Purpose: To ensure that if water were to reach a temperature slightly below pasteurization temperature and stay there, never reaching 65°C, the WAPI would not indicate a false positive.

Test: Place WAPI in heated water that is slightly below pasteurization temperature, measure the length of the wire and maintain the temperature for an extend amount of time and re-measure the WAPI length.

Supplies Needed: 1 Assembled WAPI, 1 beaker, 1 hot plate, 1 thermometer and 1 dial caliper.

Procedure:

1) Fill beaker with water and place on hot plate
2) Heat water to 60°C and maintain temperature
3) Place WAPI in 60°C water, then remove WAPI and measure length with dial calipers.
4) Place WAPI back into 60°C water and leave in water for approximately 30 minutes.
5) Remove WAPI and measure length of WAPI. Compare final value to initial value, also compare with transition temperature determined from Temperature vs. Length test.
6) Repeat steps 2 – 5 at 63°C.

TESTING RESULTS

(What follows is a description of the actual testing that was done, which was similar to the proposed testing. Only 2 samples of memory wire were used. For all tests involving temperature transition, a wire 0.092 inches in diameter (2.4 mm) was used. It was a sample given to Dale Andreatta by Tom Sponheim when they met in Seattle in January, 2010. For tests involving strength, taste, and corrosion resistance, the wire sample was obtained from the Material Science and Engineering Dept. at Ohio State with a diameter of 0.030 inches (0.75 mm). The transition temperature for this sample was greater than the boiling point. A third piece of wire, having a diameter less than 0.030 inches and a transition temperature of about 90°C that was received by Dale from Tom in Seattle was apparently lost at some point. DA)

High Cycle Testing / Checking Straightness of Wire

One primary test the team completed involved a high amount of cycles where the wire was placed in water above the transition temperature, and then cooled. Every two hundred cycles the transition temperature of the wire was checked. Because only one piece of wire with a transition temperature less than 100^{o}C was obtained, only one wire could be tested, so the transition temperature could not be compared between multiple WAPI. The transition temperature was determined by slowly increasing the temperature and measuring the distance between the ends of the wire, then finding the point at which the length appears to maximize. There were two important points to be determined with this test. The first was to determine the transition temperature; the temperature at which the wire will straighten itself back out, which ultimately indicates water has been pasteurized. The second purpose of the test was to determine if there was any change in maximum straightness or transition temperature after the wire WAPI was cycled hundreds of times. If the wire WAPI were to prematurely straighten out, this would have devastating effects for anyone who would consume the water that had been falsely indentified as pasteurized. Our goal was to ensure that with great certainty the wire would transition at or above pasteurization temperature (65^{o}C) every time the device was used.

To perform the test, the wire WAPI was first bent into a U-shape and stainless steel wire was attached to allow the WAPI to be placed near the bottom of a heated water vessel. The wire was submerged in near-boiling water, then immediately after straightening the wire was taken out, submerged in cold water and then re-bent into a U-shape. This process was repeated 200 times. After this, the WAPI was bent and submerged into water at room temperature. The WAPI was then removed and the length of the wire, from tip-to-tip, was recorded. The WAPI was repositioned in the water and the vessel was heated, increasing the temperature slowly and steadily. At specific temperatures the wire was removed from the water and additional measurements of its length were taken. Measurements were made between the tips of the wire because this was decided as the most accurate method of determining the change in the wire's length. The team then repeated this procedure five more times to reach 1200 cycles. Then the same procedure was run once more with 400 cycles having be completed rather than 200. The results are plotted in Figure 4 below and the data can be found in Table 12 of the Appendix.

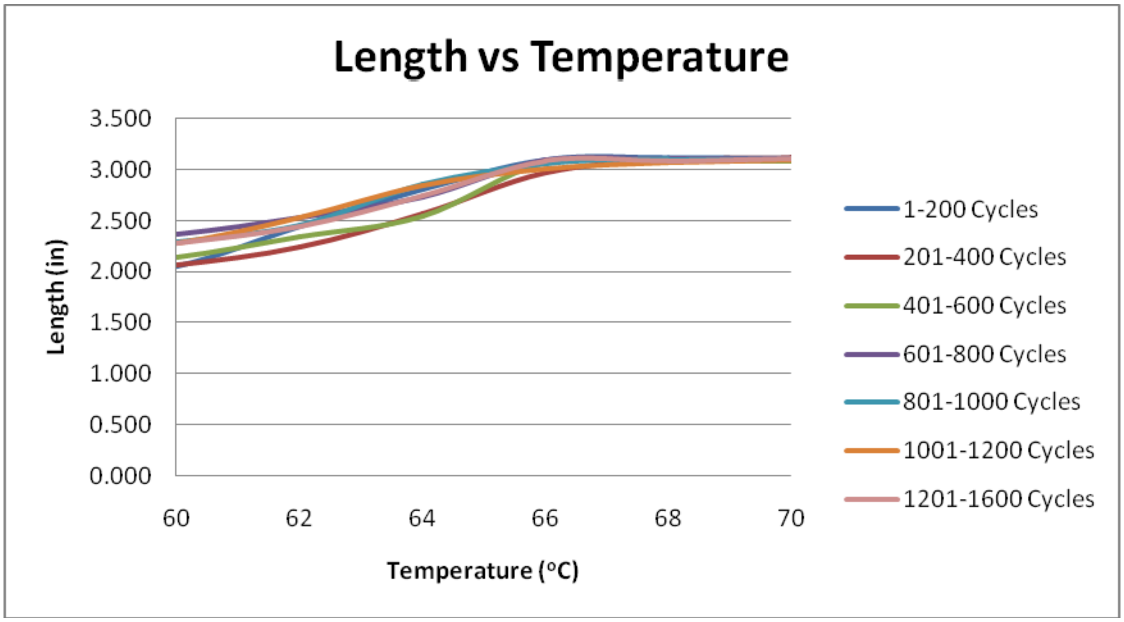

Figure 4: Plot of WAPI Length vs. Temperature for determining transition temperature

The transition temperature was taken as the temperature at which the wire reached a steady length. The transition temperature for each trial was determined from the figure above, and is tabulated in Table 4 below. The average of these transition temperatures was 66.07^{o}C with a standard deviation of 0.5624^{o}C. These values can be seen in Table 5 below. The team assumes that the true distribution of transition temperatures, given more accurate data sampling, would be approximately normal; from this assumption, a confidence interval for the transition temperature can be obtained. The team can conclude with 95% confidence that the true transition temperature is in the range of 66.07 ± 0.5624*(1.96) ^{o}C or between 64.97^{o}C and 67.17^{o}C. The expected transition temperature was between 65 and 70 degrees Celsius, and the analysis provides corresponding results.

Table 4: Final Transition Temperature for Each Trial

Trials	Transition Temperature (^{o}C)
1-200	66.5
201-400	67
401-600	66
601-800	66
801-1000	66
1001-1200	65
1201-1600	66

Table 5: Average Transition Temperature/Standard Deviation from High Cycle Testing

Average Transition Temperature (^oC)	Standard Deviation (^oC)
66.07	0.5624

In Figure 5 below, the transition temperature is plotted as a function of the number of cycles completed. The acquired data does not suggest a change in transition temperature over 1600 cycles. This is supported not only by the figure below but by how insignificant the standard deviation was found to be. From this, the group concludes that the transition temperature would not be affected over the life of the WAPI.

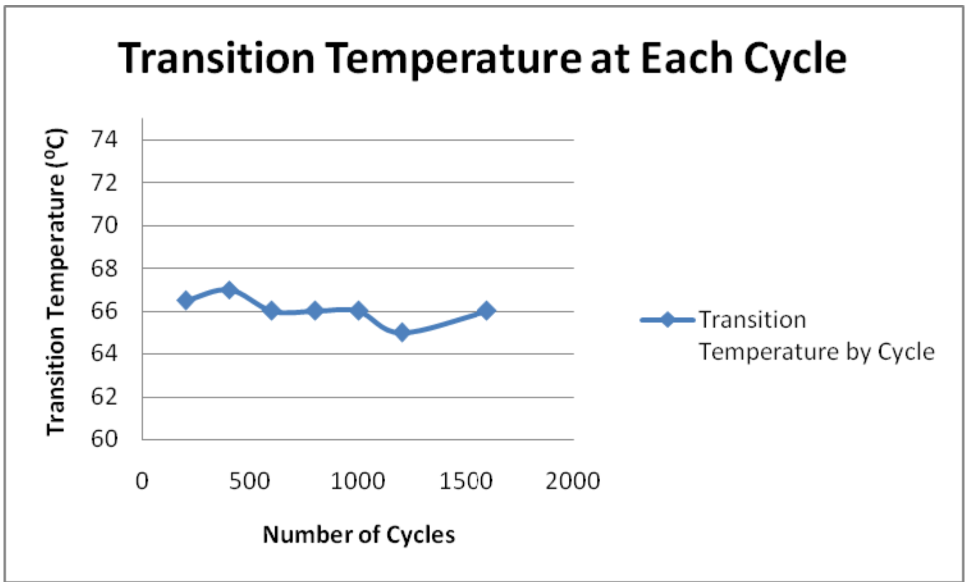

Figure 5: Transition Temperature after Each Accumulation of Cycles

In Table 6 below, the final wire length is tabulated for each number of trials that had been completed, and Figure 6 plots these values. The standard deviation of final wire length was 0.014 inches, which is a mere 0.45% of the average final wire length of 3.117 in. From this, it was concluded that the degree to which the wire straightens is not affected after 1600 cycles. The data does not support any significant relationship between number of cycles and wire length to support any claims that the level of straightness changes after a high number of cycles.

Table 6: Final Wire Length for Each Trial

Trials	Final Wire Length (in)
1-200	3.138
201-400	3.136
401-600	3.100
601-800	3.111
801-1000	3.108
1001-1200	3.112
1201-1600	3.112

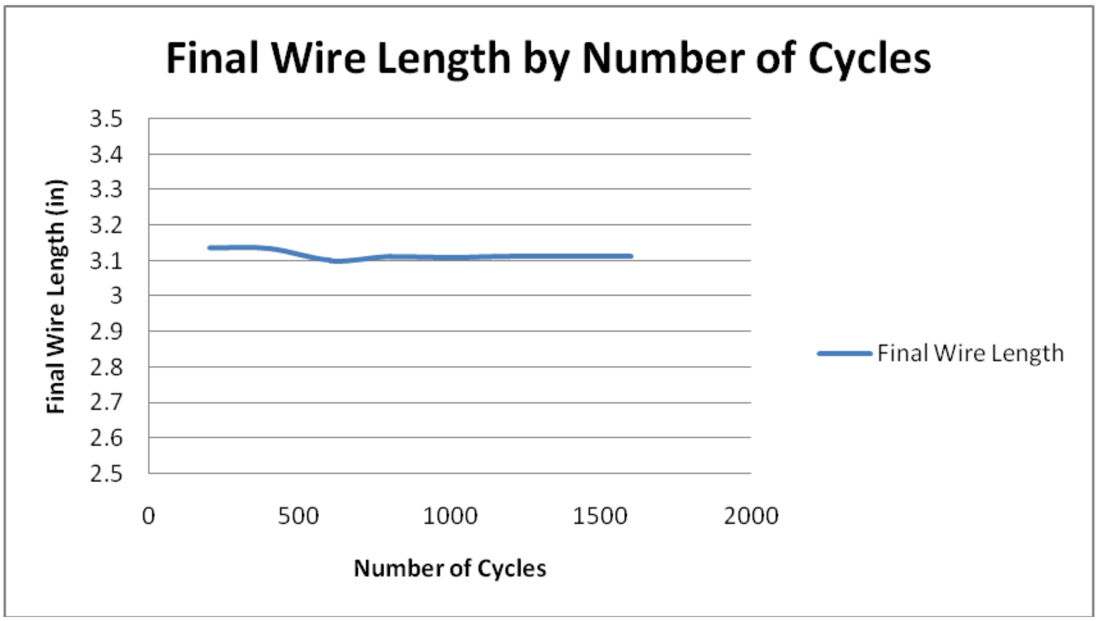

Figure 6: Final Wire Length for Each Trial

Maximum Temperature Test

A maximum temperature test was performed on the wire to determine if the transition temperature of the wire changed after the wire was heated to a very high temperature. The wire was heated in an oven to 400°F and then two straightness tests were run to determine the transition temperature of the wire. The results are shown in Figure 7 and Table 7 below.

(I was the one who proposed this test, on the basis that the inside of a solar cooker can get up to this temperature, though the water/food never gets this hot. If the WAPI slips out of the water, or

if it is left outside the water by accident, will it be permanently damaged by one cycle at this temperature? DA)

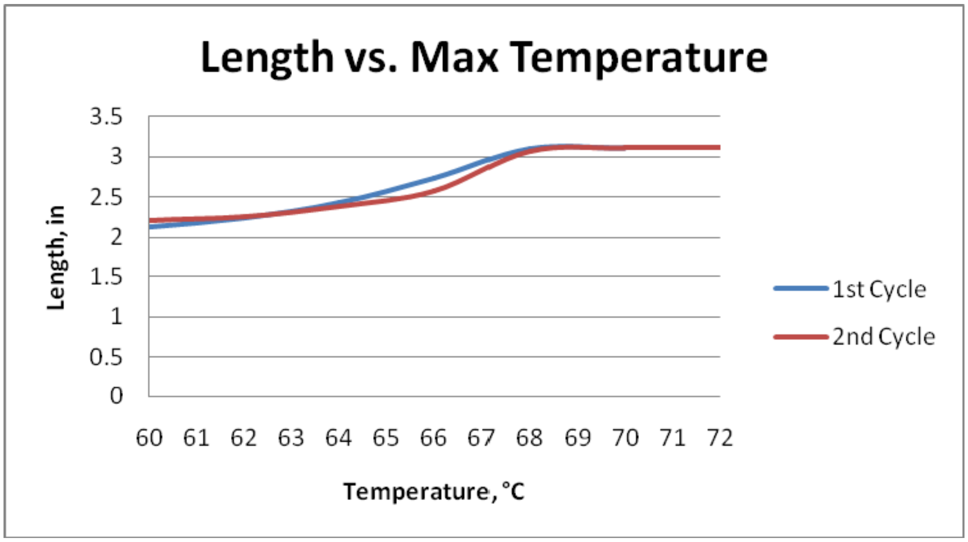

Figure 7: Maximum Temperature Test Graph

Table 7: Maximum Temperature Test Data

1st Cycle		2nd Cycle	
Temperature (°C)	**Length (in)**	**Temperature (°C)**	**Length (in)**
23	1.787	29	1.785
36	1.814	36	1.793
46	2.861	46	1.883
56	1.967	56	2.061
58	2.033	58	2.119
60	2.126	60	2.206
62	2.248	62	2.251
64	2.427	64	2.386
66	2.737	66	2.574
68	3.104	68	3.069
70	3.112	70	3.107
72	3.119	72	3.111

Observing the data above, it did appear that the transition temperature was affected by the Maximum Temperature Test, but because only two trials were run, the team felt there was not enough data to make that conclusion. In the High Cycle Testing/Checking Straightness of Wire section of this report, it was concluded that the team was 95% confident that the true transition temperature was between 64.97^{o}C and 67.17^{o}C. With only two cycles run after exposing the wire to high temperatures, the transition temperature appears to be 68^{o}C. Without more sampling, a statistically significant conclusion cannot be made. However, because the transition temperature appears to be 68^{o}C, this is a test that should be performed to a greater extent to observe whether or not the transition temperature of the wire could be affected by exposure to very high temperatures.

(The students probably should have done more tests, and this was perhaps the only area where they could have done a significantly better job. If one wanted to explore this area further, it would be best to start with a fresh sample of wire, and use it for the before and after tests. Since temperature measuring instruments can have some error, it would be best to use the same instruments for both tests as well. As it stands, we are pretty confident the transition temperature doesn't go down, thus if you overheat the wire you may be extra safe. DA)

Abuse Testing

Abuse testing was completed to ensure the wire WAPI could not be damaged through "normal" everyday usage. The material needed to produce the WAPI must be supplied by an industrialized company, but these devices are used in developing nations. For this reason the final product had to have very low cost. Just as important as the initial cost, the wire WAPI needed to be rugged enough to potentially have infinite life. This was because, the people who require these devices live off of between one and two dollars per day and could not continually purchase a low cost product. If infinite life could be realized, then it becomes possible for the people of developing nations to invest the capital in the wire WAPI.

To perform this test a WAPI was constructed, per the method found in the section titled WAPI Construction Manual, located in the Appendix. A weight stand and weights of value 1, 2 and 5 pounds were used to provide the imposed force. Vice-grips were attached to the free end of the nitinol wire and the stainless steel wire was attached to the weight stand as shown the two figures below. One member of the team used the vice-grips to lift the weight stand, while another member added weight to the stand. The maximum amount of available weight, 30 pounds (Figure 9), was added to stand without failure of the WAPI. From this the team was able to conclude that under normal conditions the wire WAPI should remain intact.

Figure 8: Vice-Grips Attached to Free End of nitinol Wire

Figure 9: Stainless Steel Wire Attached to Weight Stand

Taste Test

A double-blind taste test was performed to determine if using the wire WAPI had an adverse effect on the taste of the water. Two members of the group blindly tasted water that had been heated with a WAPI in it and water that had been heated without a WAPI inside. One group member could not even begin to venture a guess as to which one had been used with the WAPI, and thought that both water samples tasted the same. The other thought that the non-WAPI water tasted worse than the WAPI water. Because neither group member could determine which water sample was which, the group concluded that water exposed to a WAPI does not have an adverse effect on water taste.

Corrosion Test

A corrosion test was performed for the same reason as the abuse test; to ensure that the wire WAPI could potentially provide infinite life. The scope of the team's time, to test for corrosion, was limited by both the overall time allotted for testing, 10 weeks, and lack of nitinol wire for WAPI construction. For these reasons, the corrosion testing could only be performed for one month, and was done so with a sample from the Material Science Department at The Ohio State University. The results from the test were able to provide very promising data that suggested long-life was achievable.

Two dark glass bottles were obtained and filled with water from two different sources. One bottle was filled with tap water and the other was filled with water from the Olentangy River, with the bottles labeled respectively. The Olentangy River was chosen because the team felt that this would allow for the most realistic field test sample and tap water was used for comparison. WAPI were assembled and dial calipers were used to measure the diameter of the nitinol wire before placing them into the bottles. The bottles were placed on the roof of one group member's house where they could be heated by the sun and be exposed to the environment. The bottles were left untouched, on the roof, from March 24th to May 22nd, 2010. Once retrieved, the WAPI were removed from the bottles and the diameters of the nitinol were again measured.

The results from this test are found in Table 8, which shows that there was no corrosive loss to the nitinol wire. The nitinol wire from the Olentangy River bottle did feel rough to the touch, because an oxidized layer had formed on its surface, thus protecting it from further corrosion. Additionally, there was some build-up on the aluminum compression stop which joined the stainless steel and nitinol wires (Figure 10). This build-up also only appeared on the Olentangy River water sample, and the team was not certain if this was caused by corrosion or just bacteria growth. The team did conclude that the build-up should be neglected, because the WAPI would almost never be placed in a water vessel and left there for month long period since the water would be needed for consumption. Also, whenever the WAPI is removed from a water vessel, it would most likely be allowed to dry before reusing. Overall, the team concludes that corrosion would not be a hindrance to infinite life.

Table 8: Results of Corrosion Test

Water Source	Initial Diameter	Final Diameter
Tap Water	0.030 in	0.030 in
Olentangy River	0.030 in	0.030 in

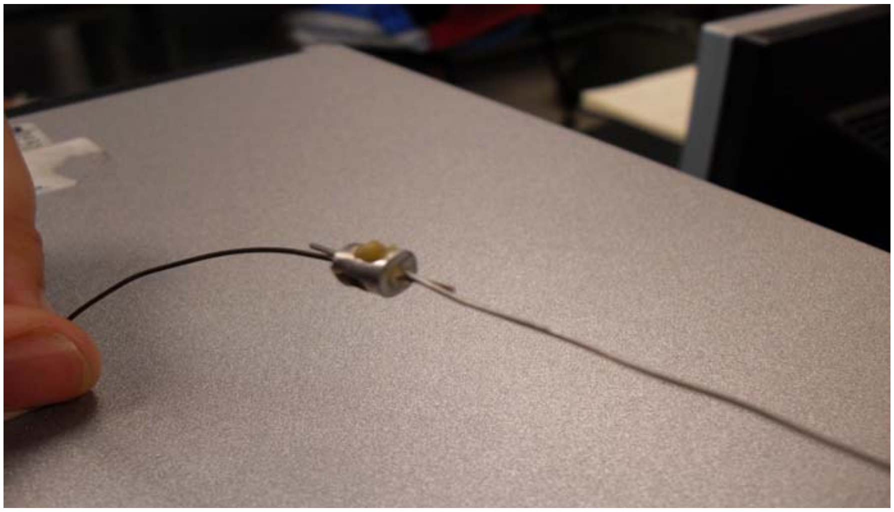

Figure 10: Build-up on Aluminum Compression Stop from Olentangy River WAPI Sample

Static Temperature Test

The static temperature test was performed to ensure that the WAPI would not display a false reading of being straight, if the wire never reached a pasteurization temperature of 65°C. Temperatures of 60°C and 63°C both where taken for 30 minutes to ensure that if the WAPI was left at a temperature just below the pasteurization level, for an extended period of time, the wire would remain a constant length.

The test was performed using lab equipment where water was held at a constant temperature for the time duration. When the water was heated up to the proper temperature, the wire was placed into a beaker and the initial time and length of the wire was recorded. As time passed the beaker was manually removed from the hot plate to aide in the constant temperature control. After the 30 minutes had passed, the wire was removed from the water and measured for length. This length was the compared with initial length and the pasteurization temperature length.

After performing the test at 60°C and 63°C the results concluded that the wire would not indicate a false positive reading. The results can be seen in Table 9, which show that the wire measured before the 30 minute bath was nearly the same length after the bath. The small discrepancies present in these results were mostly likely the cause of human error, because the temperature would occasionally rise slightly above the test temperature. Even assuming that there was no human error present in that data, the temperatures at which this test was performed, were in the area where the length of the wire would expand the most. Therefore a large change in wire length would have needed to be present to conclude that a false positive could be achieved.

Temperature, (°C)	Length Before Bath (in)	Length After Bath (in)	Time Duration (min)
60	2.083	2.091	30
63	2.264	2.278	30

Table 9: Static Temperature Wire Lengths

COST OF WIRE WAPI

The cost of a WAPI had to be kept to an utmost minimum, because as previously mentioned, these devices will be used by people of developing nations and most likely purchased by non-profit organizations. Additionally, the WAPI needed to be easy to assemble and not require expensive tooling. The current WAPI design of wax in a vial had a cost of approximately $0.81, therefore the goal of our team was to match or reduce this price with the wire WAPI.

For the cost analysis of the wire WAPI many assumptions had to be made. The cost of the material used to produce each WAPI was based off of the supplier our team used, which was *mcmaster.com*. The only item not purchased from McMaster-Carr was the nitinol wire, which was never actually purchased, but would have been sourced from Johnson-Matthey. The cost of the WAPI did not include the basic tools, hammer and punch, as these would be supplied by an outside source. There would be no labor cost associated with producing the final product, as this would be done by either the local villagers or a non-profit organization. Each WAPI would need 18 inches of stainless steel wire, 3 inches of nitinol wire, 1 aluminum compression sleeve. Additionally, one shaft collar will be needed per household. Because most WAPI are used in Africa, the size of a household was determined from African census data. This data was hard to obtain, so an assumption for household size was based off of a single paper with the pertinent information tabulated in Table 10. The final assumption was that each person would need one WAPI, because clean water production is normally done on a per person basis and not mass produced. The results of the cost analysis are tabulated below, with an average final cost of $0.40 per WAPI.

Table 10: African Census Information (Plange-Rhule)

Village Type	Households	Persons per Household	Total per Village
Rural	750	9	6597
Semi-Urban	710	15	10,368

Table 11: Cost Analysis of Wire WAPI

WAPI Item	Units per Package	Cost per Package	Cost per WAPI
Compression Sleeve	50	$7.39	$0.1478
Shaft Collar	1	$0.65	$0.0722 / $0.0433*
Stainless Steel Wire	3640 feet	$103.62	$0.0427**
Nitinol Wire	1 foot	$0.60	$0.15***
		Total Cost	**$0.41 / $0.38**

*Based on shaft collar per household (see Table 10 for village data)

**Based on 18 inches of wire per WAPI

***Based on an email quote of $0.60 per foot and 3 inches were needed per WAPI

(I'm not sure why the students assumed one shaft collar per household, the shaft collar is merely used as a tool to build the WAPI. The WAPI's would be built in a workshop, not in the home where they are to be used, so the cost of the shaft collar could be removed from the above table. DA)

CONCLUSION

It is clear from the results obtained in this report that each of the necessary constraints for the memory wire WAPI were met. This indicator could easily be used in either solar or flame heated applications, because the stainless steel wire attachment allowed the WAPI to be placed at any depth within a vessel. The stainless steel wire allowed for a depth of up to 18 inches to be achieved. The nitinol wire was flexible at low temperatures allowing it to be easily bent into any shape and could therefore be inserted into a vessel with any size opening. Additionally, because the memory shape yielded a straight wire, the WAPI was ensured to always be straight after pasteurization, allowing for easy removal from any size vessel opening.

Some of the more vital constraints of the memory alloy WAPI were the transition temperature, life, and overall cost. The transition temperature of the WAPI remained unchanged, even after the many different tests were run, meaning the risk of a false positive would never be realized. The attachment configuration was durable enough to withstand at least 30 pounds of force, providing the conclusion that under normal conditions the wire WAPI would not fail from external forces. Additionally, it was observed that corrosion would not provide premature failure. Finally the average cost of the wire WAPI was found to be approximately half the cost of older WAPI designs, well within the goal of the team. All of these individual findings culminate to the overall conclusion that the wire WAPI is a definite practical replacement for older water pasteurization indicators.

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APPENDIX

WAPI CONSTRUCTION MANUAL

There were six items needed for the construction of a wire WAPI: 1 hammer, 1 punch, 1 three inch section of nitinol wire, 1 eighteen inch section of stainless steel wire, 1 aluminum compression stop sleeve and 1 set screw shaft collar (Figure 11).

Figure 11: Items Needed for WAPI Construction

To begin construction the set screw was removed from the shaft collar, this allowed for the punch to be inserted in this hole. Secondly, the aluminum compression stop sleeve was placed concentrically inside the shaft collar (Figure 12). Ideally the outer diameter of the compression stop would be the same size as the inner diameter of the shaft collar. This configuration was needed so the compression sleeve would not radially deform and only a point contact would be provided from the punch.

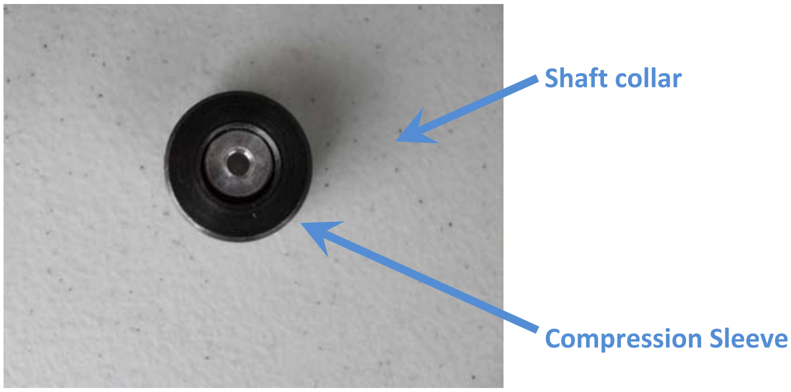


Figure 12: Compression Sleeve Concentrically Inside the Shaft Collar

The next step involved placing the two wire sections (nitinol and stainless steel) inside the compression sleeve as displayed in Figure 13.

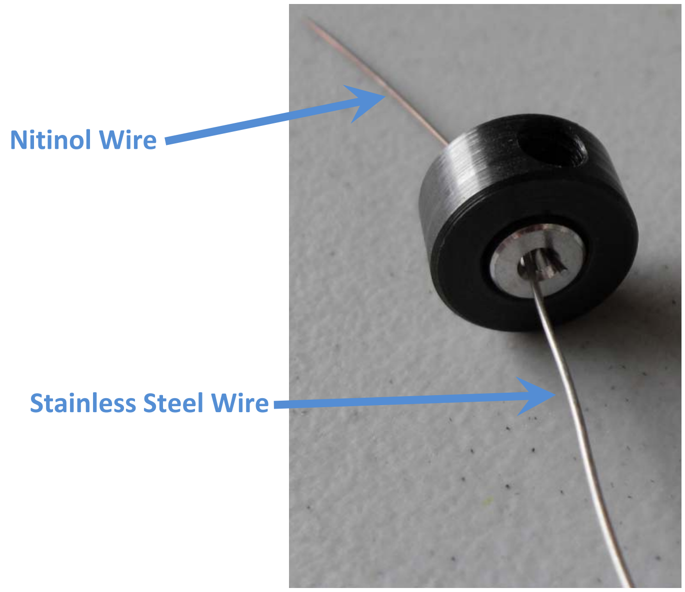


Figure 13: Nitinol and Stainless Steel Wires Place Inside Compression Sleeve

Finally, the punch was inserted into the hole left behind by the remove set screw and the hammer was used to drive the punch into the compression stop. This was done in two different locations because the compression sleeve was meant for the larger diameter wires the team was supposed to receive. The final assembly is shown below.

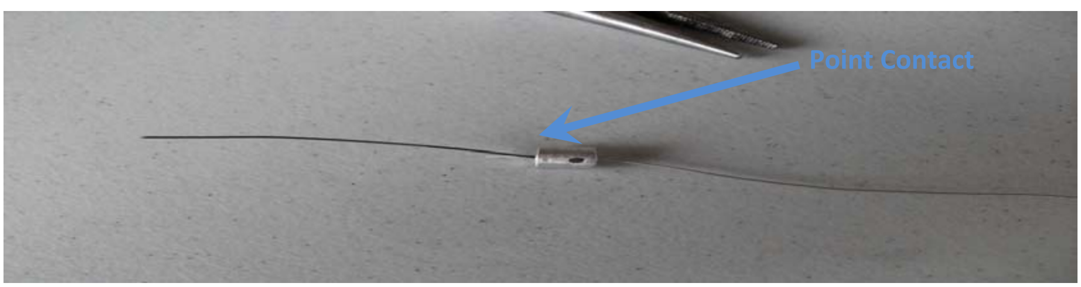


Figure 14: Complete Assembly of Wire WAPI

Alternative WAPI Construction Method

Another, much simpler, method for attaching the nitinol and stainless steel wires together was done by eliminating the need for a shaft collar and punch. In this case, the hammer was used to simply flatten the compression sleeve, sandwiching the wires between the entire sleeve instead of having a point contact, Figure 15.

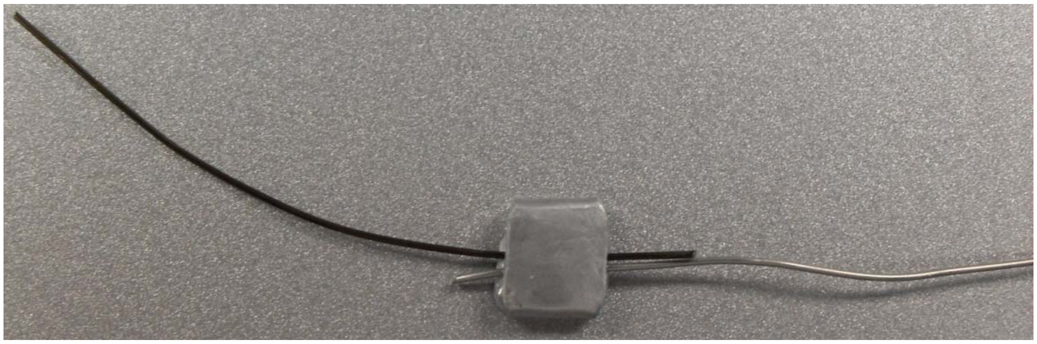
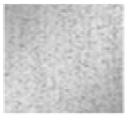


Figure 15: Simple WAPI Attachment Method

This configuration could be easily completed without the hammer as well, because all that was required were two hard objects, one to set the WAPI on and the other to smash the compression sleeve flat. The advantages here were that all manufactured tools and the cost of the shaft collar could be eliminated. The disadvantage was the connection could not support nearly the same force; the nitinol slipped out with less than 20 pounds of force applied.

MATERIAL INFORMATION (from mcmastercarr.com)

Stainless Steel



Part Number: 8860K14	$6.70 Each
Material	Multipurpose Stainless Steel (Type 302/304)
Finish/Coating	Matte
Shape	Wire
Wire Type	Standard
Wire Diameter	.032"
Wire Diameter Tolerance	±.0005"
Tolerance	Standard
Test Report	Without Test Report
Gauge	20 AWG
Wire Form	1/4 lb. Spool
Approximate Feet per Coil	91'
Condition/Temper	Soft Temper
Hardness	Not Rated
Tensile Strength	75,000 to 120,000 psi
Maximum Temperature	550° F
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM A555, ASTM A580

Figure 16: Stainless Steel Wire Information Provided by McMasterCarr.com

Compression Sleeves and Tools for Wire Rope *(Continued from previous page)*

Stop sleeves create a stop at the end of the wire rope. *Note:* Stop sleeves are not for lifting applications.

					SLEEVES			COMPRESSION TOOLS					
								Single Diameter			Multidiameter		
For Rope Dia.	OD	OD (Compressed)	Sleeve Length	Required No. of Compressions	Pkg. Qty.		Per Pkg.	(A)		Each	(A)		Each
Stop Sleeves and Compression Tools—Not for Lifting													
Aluminum Sleeves for Steel and Galvanized Wire Rope													
1/16"	7/32"	3/16"	3/16"	1	50	3914T11	$7.30	18 3/8"	3377T12	$159.75	20"	3582T1	$185.02
3/32"	11/32"	9/32"	5/16"	1	50	3914T2	7.39	—	—	—	18 3/4"	3582T22	159.75
1/8"	11/32"	9/32"	5/16"	1	50	3914T3	7.16	—	—	—	18 3/4"	3582T22	159.75
5/32"	13/32"	11/32"	5/16"	1	50	3914T4	8.21	—	—	—	18 3/4"	3582T22	159.75
3/16"	7/16"	11/32"	5/16"	1	50	3914T5	9.05	—	—	—	18 3/4"	3582T22	159.75
1/4"	21/32"	19/32"	11/16"	2	10	3914T6	5.04	33"	3377T18	360.60	34"	3582T6	448.53
5/16"	11/16"	19/32"	11/16"	2	10	3914T7	5.77	33"	3377T18	360.60	34"	3582T6	448.53

Stop Sleeve

Compressed Stop Sleeve

Figure 17: Aluminum Compression Stop Sleeves (Item #3914T2 Was Used) Information Provided by McMasterCarr.com

Shaft Collars

Part Number: 9414T8	$0.65 Each
Type	Set Screw
System of Measurement	Inch
Material	Steel
Steel Material	Carbon Steel
Finish	Black-Oxide
Bore Size	3/8"
Outside Diameter	3/4"
Width	3/8"
Screw Size	1/4"-20
Set/Cap Screw Material	Alloy Steel
Specifications Met	Not Rated

Figure 18: Set Screw Shaft Collar Information Provided by McMasterCarr.com

ADDITIONAL TEST DATA

High Cycle / Checking Straightness as a Function of Temperature Data

Table 12: High Cycle / Straightness as a Function of Temperature

1-200 Cycles		201-400 Cycles		401-600 Cycles	
Temp, °C	Length, in	Temp, °C	Length, in	Temp, °C	Length, in
22	1.753	25	1.705	24	1.881
36	1.746	36	1.721	36	1.892
46	1.769	46	1.757	46	1.907
56	1.840	56	1.923	56	1.989
58	1.930	58	1.972	58	2.027
60	2.054	60	2.065	60	2.135
62	2.836	62	2.238	62	2.339
64	2.800	64	2.563	64	2.543
66	3.100	66	2.975	66	3.067
68	3.118	68	3.100	68	3.086
70	3.115	70	3.119	70	3.080
72	3.138	72	3.136	72	3.100

601-800 Cycles		801-1000 Cycles		1001-1200 Cycles	
Temp, °C	Length, in	Temp, °C	Length, in	Temp, °C	Length, in
27	1.709	28	1.890	24	1.750
36	1.772	36	1.915	36	1.809
46	1.822	46	1.954	46	1.835
56	2.046	56	2.118	56	2.014
58	2.281	58	2.180	58	2.178
60	2.370	60	2.290	60	2.275
62	2.531	62	2.460	62	2.525
64	2.736	64	2.850	64	2.849
66	3.089	66	3.060	66	3.009
68	3.103	68	3.100	68	3.064
70	3.110	70	3.102	70	3.100
72	3.111	72	3.108	72	3.112

1201-1600 Cycles

Temp, ^{o}C	Length, in
24	1.811
36	1.851
46	1.898
56	2.076
58	2.150
60	2.284
62	2.442
64	2.739
66	3.083
68	3.081
70	3.110
72	3.112