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THESIS

BUILDING AND TESTING AN INCOMPRESSIBLE THERMALLY INSULATING COLD TEMPERATURE DIVING WETSUIT

by

Shane L. Martin

September 2020

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13. ABSTRACT (maximum 200 words)

Thermal protection for divers is critical and needs improvement. The goal is to have a full wetsuit that will insulate the human body from the colder temperature of the water and the depth that a diver is submerged. I designed, fabricated, and built a fully thermal passive insulation wetsuit using composite material based on microspheres to be able to comfortably fit on a human to minimize restriction while diving and performing duties underwater. During testing in the open ocean, the composite wetsuit was proven to be superior to neoprene wetsuits by several degrees Fahrenheit. This composite wetsuit has the advantage of a three millimeter neoprene wetsuit for mobility and performs better than a seven millimeter neoprene wetsuit for warmth. By improving divers' thermal protection in water, the composite wetsuit will enhance their job performance and increase the amount of time they can spend underwater.

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BUILDING AND TESTING AN INCOMPRESSIBLE THERMALLY INSULATING COLD TEMPERATURE DIVING WETSUIT

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ABSTRACT

Thermal protection for divers is critical and needs improvement. The goal is to have a full wetsuit that will insulate the human body from the colder temperature of the water and the depth that a diver is submerged. I designed, fabricated, and built a fully thermal passive insulation wetsuit using composite material based on microspheres to be able to comfortably fit on a human to minimize restriction while diving and performing duties underwater. During testing in the open ocean, the composite wetsuit was proven to be superior to neoprene wetsuits by several degrees Fahrenheit. This composite wetsuit has the advantage of a three millimeter neoprene wetsuit for mobility and performs better than a seven millimeter neoprene wetsuit for warmth. By improving divers' thermal protection in water, the composite wetsuit will enhance their job performance and increase the amount of time they can spend underwater.

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LIST OF ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
°F	degrees Fahrenheit
3D	three dimensional
BCD	Buoyancy Control Device
FSW	Feet Sea Water
mm	millimeter
PDMS	polydimethylsiloxane
PSI	pounds per square inch
rpm	rotations per minute

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I. INTRODUCTION

A. BACKGROUND

Diving has been around for thousands of years and will continue for thousands of years as humankind explores the vast depths the ocean has to offer. Humans began diving mainly for the purpose of food, which then expanded to trade with the fascinating finds of the ocean, like pearls and seashells.

The Ancient Greek historian Herodotus recounts one of the earliest recordings of divers in his *The Histories.* Herodotus writes of a man named Scyllias who was used by the Persians to dive on wrecked ships off the Pelion peninsula in Greece. He found valuables for the Persians and took some for himself as well. In one legend, he escaped the Persians by diving and swimming underwater for a distance of 15 kilometers to bring the Greek valuable information on their current enemy, the Persians [1]! Whether this tale was true or not, Scyllias has continuously intrigued humankind to dive for both military functions and salvage work.

Since most civilizations were founded near water, trade naturally began via naval vessels. These vessels were often lost at sea, particularly in the ancient world, and so divers were employed to find and salvage these vessels and were paid based on depth. Even back then they knew the dangers and increased ability with deeper depths.

B. CHALLENGES

Diving brings about many natural challenges. Finite oxygen amounts limit bottom time and nitrogen levels in the body bring inherent dangers. Water temperature can also be perilous due to the high risk of hypothermia which can cause severe damage to the human body.

Hypothermia occurs when the core temperature of a human drops below 95 degrees Fahrenheit and it is much more common in water than in cold air [2]. This is due to the fact that the thermal conductivity in water is around 0.6 W/[m*K] around 20 degrees Celsius [3], while air's thermal conductivity is 0.026 W/[m*K] at the same temperature [4]. This means that water removes heat from the human body 23 times faster than it would in the open air. As can be shown in Figure 1, human survival in cold water is not long.

How long can a person survive in cold water?

Water Temperature		Expected Time Before Exhaustion or Unconsciousness	Expected Time of Survival
(°F)	(°C)		
32.5°	0.3°	< 15 minutes	45 minutes
32.5–40°	0.3–4.4°	15 – 30 minutes	30 – 90 minutes
40–50°	3.3–10°	30 – 60 minutes	1 – 3 hours
50–60°	10–15.6°	1 – 2 hours	1 – 6 hours
60–70°	15.6–21.1°	2 – 7 hours	2 – 40 hours
70–80°	21.1–26.7°	3 – 12 hours	3 hours – indefinite
> 80°	> 26.7°	Indefinite	Indefinite

Figure 1. Expected time of survival in cold water. Source: [2].

Traditionally, divers counter hypothermia by wearing neoprene wetsuits and dry suits. Both have their advantages and disadvantages and need to be used in the correct situation.

C. SOLUTIONS

Neoprene wetsuits are the standard solution for keeping divers warm while they carry out their work. Also called polychloroprene, neoprene is produced by the polymerization of the chloroprene [5]. To make the wetsuit waterproof, the neoprene is made to be closed-cell with nitrogen gas bubbles throughout the wetsuit [5]. Water, however, often gets inside the wetsuit due to the openings at the hands, feet, and neck. When the water gets inside the wetsuit, it is quickly warmed by taking heat from the human body. This can help with insulation and warm the human body temporarily, but that water continues to surge in and out of the wetsuit. This means the human body is continually supplying heat to warm the water. This water cycling and heat loss through the wetsuit causes the diver to slowly lose body temperature. Dry suits, on the other hand, keep water out completely, but these dry suits are very cumbersome and not easy to dive in whatsoever. They also still allow heat loss through the dry suit material to the ambient water.

Pressure also causes problems with neoprene material. With the increase in pressure, the neoprene starts to compress, and so does the size of the air bubbles. This results in a drastic loss of insulation as the diver descends. We want to correct this problem by finding a material that will not shrink like neoprene but will thermally insulate the body.

Researchers have been trying to solve this problem since the 1970s through the use of glass microspheres. They were able to prove that glass microspheres at depths of 1000 FSW had less than a 3% reduction in cell volume [6]. Due to a lack of high-quality manufacturing, this idea was disregarded until technology advanced enough to easily make high-quality, consistent pieces. Now, industry consistently makes stronger high-quality glass microspheres that will result in less breakage. Minimal breakage is critical because when the microspheres break, it renders the material useless for thermal insulation. The microspheres used in this thesis are from 3M and are called "K1 Glass Bubbles." These have a thermal conductivity of 0.047 W/[m*K] at 20° Celsius, which is just under twice the amount of thermal conductivity of air at the same temperature, and they can withstand the pressure at depths of just over 500 feet [7].

Another NPS student, Brown [8], evaluated whether these glass spheres are more effective than neoprene. To do this, he mixed a pre-polymer with the glass beads to create a semi-flexible piece that still retained the glass microspheres unbroken. With his research, it was shown that in the lab at similar depths, the composite material thermally insulated three times better than neoprene did, which can be seen in Figure 2. With the theory and material in the lab proven effective, it was time to make a prototype wetsuit to test.

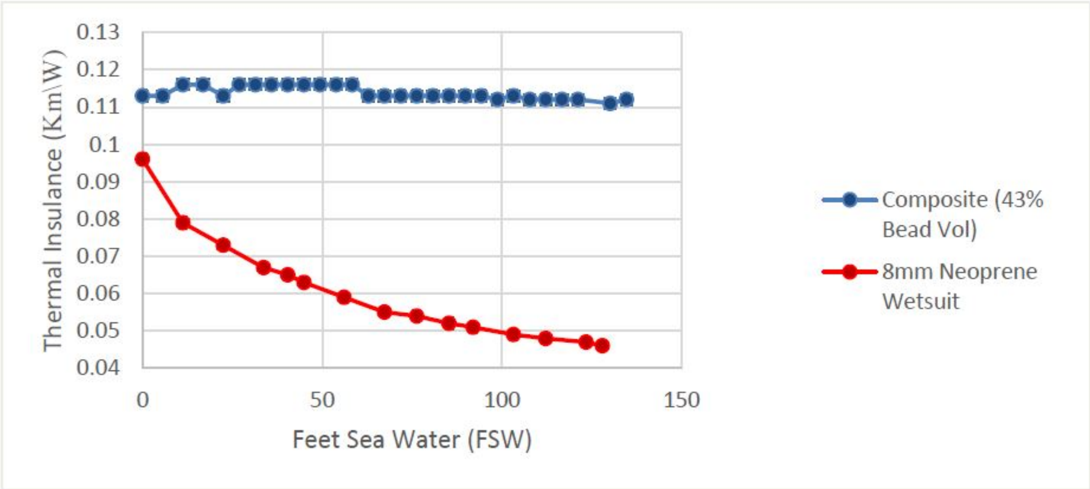

Figure 2. Thermal insulance of neoprene and composite as a function of depth. Source: [8].

D. CONSTRUCTING THE COMPOSITE PIECES

While working on his thesis, LT Aaron Demers [9] , a former colleague at the Naval Postgraduate School, constructed the composite pieces that I will use for the testing of the final wetsuit. By taking what was found in Brown's research, Demers and I started building the composite pieces. We began by taking a 3-D image of each of us wearing a wetsuit so we had a baseline for the mold. Once this had happened, we used two computer programs to start making the molds, MeshLab and SolidWorks. MeshLab was used to cut the pieces that we wanted to make a mold of. This piece was then sent to SolidWorks where the mold is made [9].

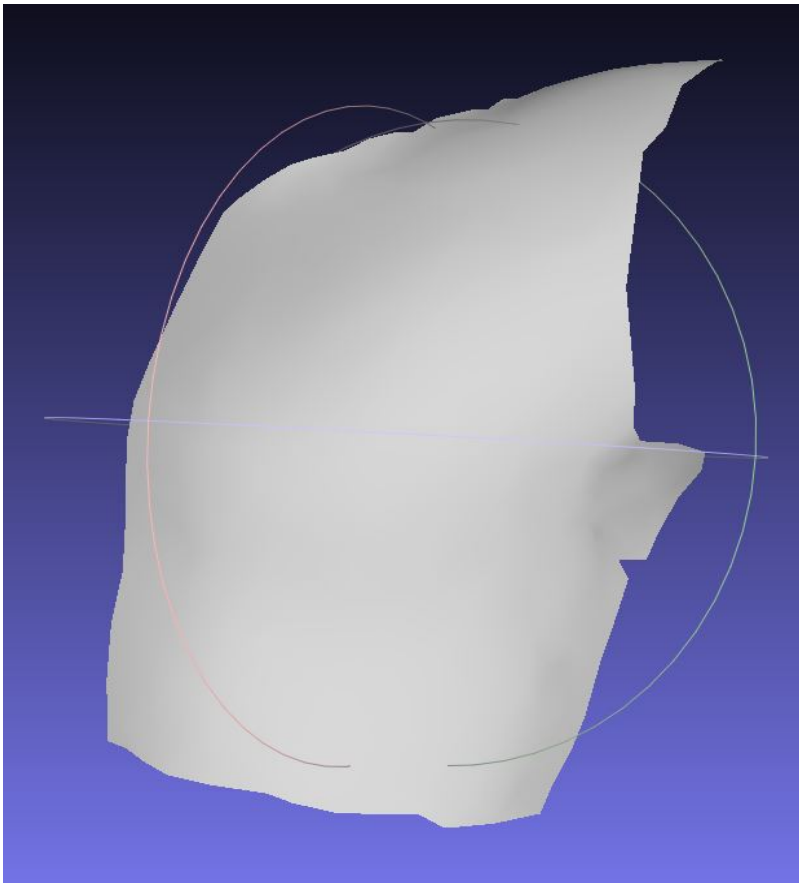

Figure 3. Left pectoral piece from MeshLab ready to be imported to SolidWorks. Source: [9].

In SolidWorks, the mold is made by duplicating the piece and offsetting each piece by eight mm. This offset defines the thickness of the mold. This size was chosen due to most wetsuits being eight mm thick. Then, each piece is extruded outward to start forming a box, since the eight mm separation will be used to make the pieces we need for the wetsuit. The top box of the mold has a rectangular box placed on it to ensure that the eight mm separation remains when the top of the box is placed into the bottom of the box. Holes are then placed throughout the top of the box to ensure even settling of our material and proper venting. With the mold done, as shown in Figure 4, it was time to make the piece.

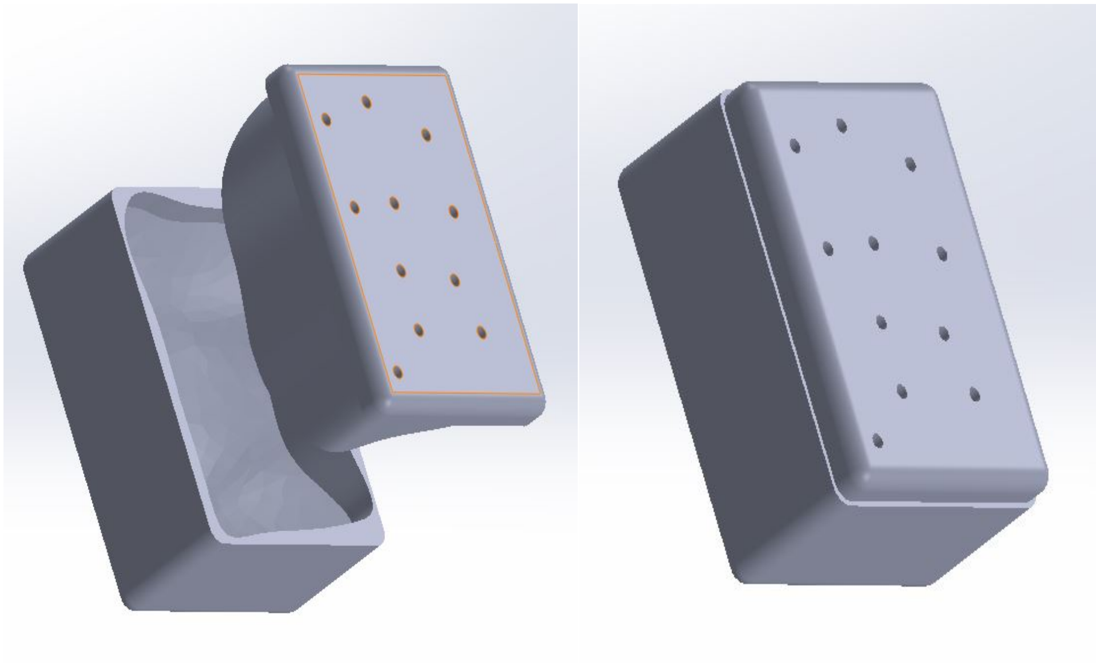

Figure 4. Final mold (left) and rejoined together with the eight mm gap on the inside (right). Source: [9].

The first step was to mix a two-part pre-polymer, Sylgard 184 polydimethylsiloxane (PDMS), which consisted of an elastomer base and an elastomer curing agent. This is mixed in a 10:1 ratio, base to curing agent, and placed in a ARE-310 rotary mixer at 1500 rpm for four minutes.

Figure 5. THINKY rotary mixer with jar inserted and set spin duration to be four minutes and spin frequency to 1500 rpm. Source: [9].

The ARE-310 rotary mixer is produced by THINKY Inc. of Japan. The rotary mixer mixes this material uniformly and quickly due to the revolution and the rotation of the container, a 45-degree tilt. The revolution uses a centrifugal force to cause the material to move away from the center [10]. The rotation of the container causes material flow with the 45-degree tilt, causing it to be three-dimensional (3D). This can be seen in Figure 6. Combining these techniques allowed our material to be thoroughly mixed.

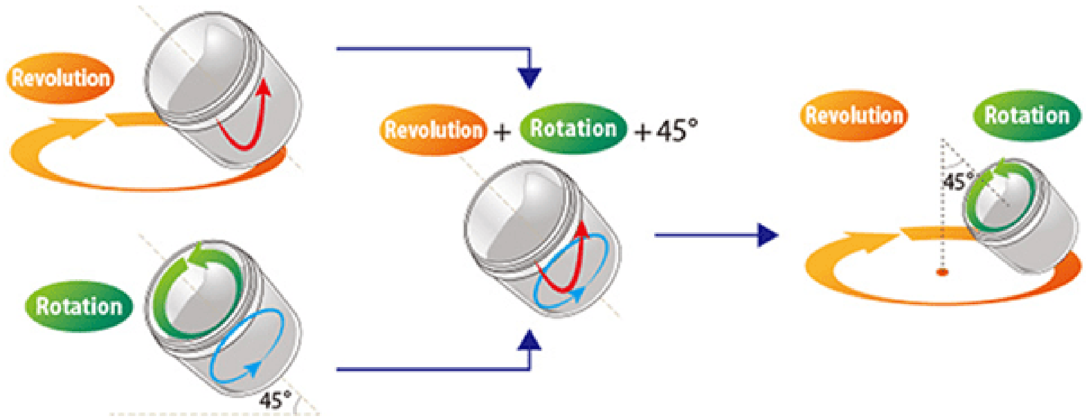

Figure 6. An illustration of how the ARE-310 planetary centrifugal mixer works. Source: [10].

We then added the glass microspheres at an almost 1:1 ratio with the pre-polymer. This was again combined in the THINKY rotary mixer at the same rpm and time as before. This greatly reduced the amount of breakage that could happen to our glass microspheres. After confirming that glass microspheres were evenly distributed within polymer, we degassed the material by removing the air pockets in the mixture to prevent open air pockets in the mold that would compromise the integrity and insulation of the wetsuit. Once degassed, the material was then poured into the bottom portion of the mold. The top of the mold was then carefully placed into the bottom portion and pressed down to ensure the finished mold kept the eight mm thickness that it was designed to have.

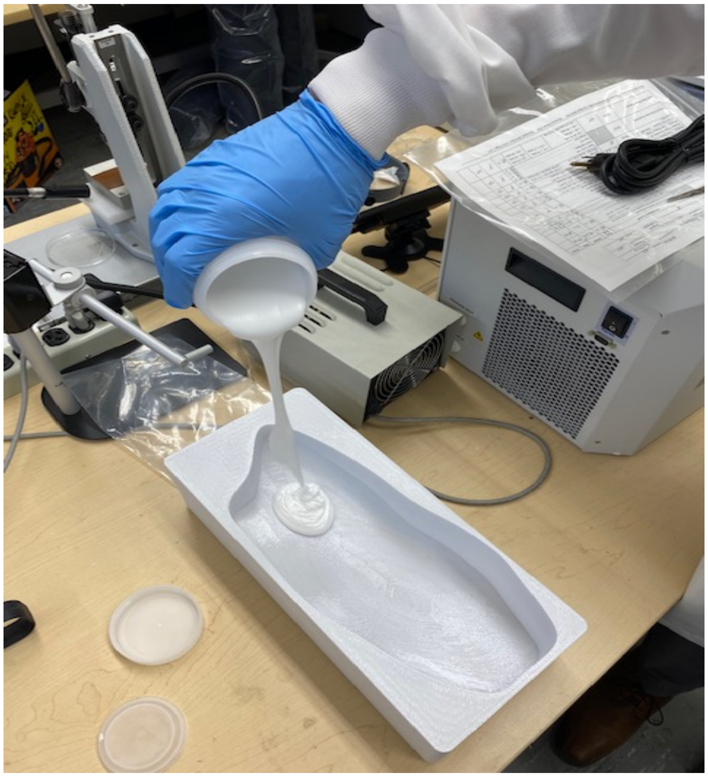

Figure 7. Demers pouring liquid composite into the bottom piece of a mold. Source: [9].

The liquid composite was then cured in the mold. Curing is the process of the PDMS and the glass microspheres becoming a solid, and this is done in one of two ways. To accelerate the curing process to enable building more composite pieces in the same day, we placed the mold in an oven at 80° C to cure in two hours. Normal curing time, at room temperature, 20° C, is 24 hours.

Figure 8. The author is shown removing composite pieces from the mold. Source: [9].

When the piece was cured, we peeled apart the top and bottom mold pieces and pried out the final piece. Afterward, we easily cut away the extra material that escaped on the sides and the vent holes in the top mold piece. We now had our composite piece.

Figure 9. A final composite piece, front and rear, appendages removed.
Source: [9].

With support from Demers, a total of seven molds were created: left and right pectoral, abdominal section, left and right upper back, lower back, and right thigh. Only the right thigh was created because of body similarities between the left and the right thigh. We also used the same mold for both hamstrings and for the outer portion of the lower leg. This saved time and money in creating more composite pieces to cover more of the human body. The following tests used a total of 12 composite pieces to cover 72% of the human body. This estimate was based on the Rule of Nines used in medicine to describe areas of burns [11].

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II. ADHESIVES

A. IDEAS FOR ADHESIVES

Once we started making composite pieces, we needed to determine a way to attach the composite pieces to the wetsuit. We decided a simple solution would suffice for the prototype.

1. Velcro / Tape

Our first idea was to use Velcro or tape to attach the composite pieces to the wetsuit. This seemed logical. Velcro patches are typically sewn onto wetsuits to place items. Our first attempts failed as we discovered that the Velcro did not stick to our composite material. We made multiple adjustments, including cleaning the composite, placing a weight on top of the Velcro to help with adhesion, and even using the inside of the wetsuit, but with no success. We then attempted tape and reached the same conclusion. Nothing was sticking to our composite material, likely because most of the composite surface is glass, which is chemically quite inert.

2. Glue

We then attempted to use glue as the next logical adhesive. We tried commercial glues like Elmer's Glue, Gorilla Glue, wetsuit cement, and Loctite to hold the composite material to the neoprene wetsuit, but they all failed. The glue stuck to the neoprene, but not the composite material.

Figure 10. Glue adhesives that were used to adhere neoprene and our composite material.

3. Lord Corporation

We then moved away from the commercial glue and tried Lord Corporation: Adhesives, Coatings, Vibration, and Motion Control. By describing our composite material to Lord Corporation and our plan to attach the composite pieces to neoprene, they instructed us to order Lord 7650 and 7701, which can be seen in Figure 11. We also ordered Lord 7542 A/B, 7545 A/B, and 310 A/B, but these require two different applicator guns that were not originally ordered. By the time we received the material, it was too late to wait again for the applicator guns to be ordered. These will be tested at a later time.

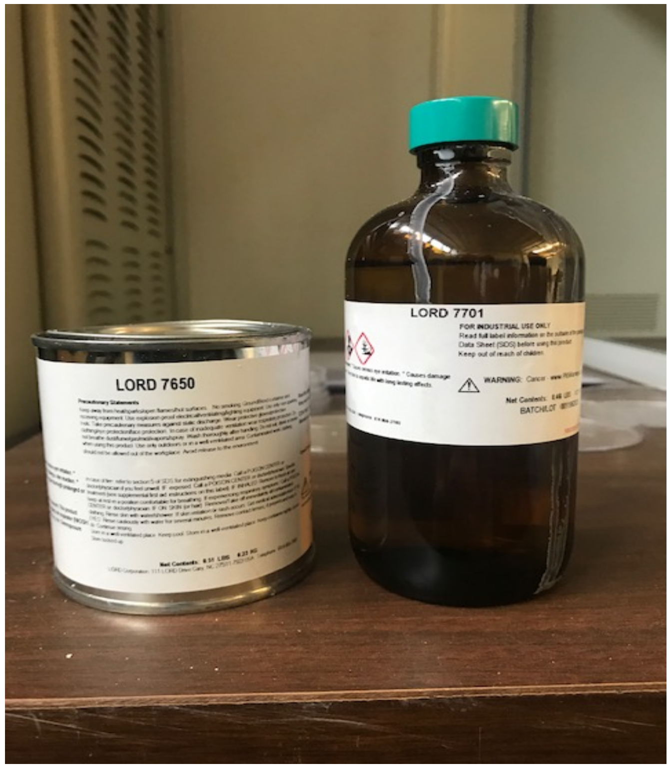

Figure 11. Lord Corporation adhesives were used to adhere the composite material to the neoprene.

Once we received the materials, we started experimenting by applying the material. We took multiple approaches, leaving the material to cure for up to 24 hours. Every new approach continued to bring about the same results— the material cured together but only stuck to the neoprene. Everything continued to peel off of the composite material.

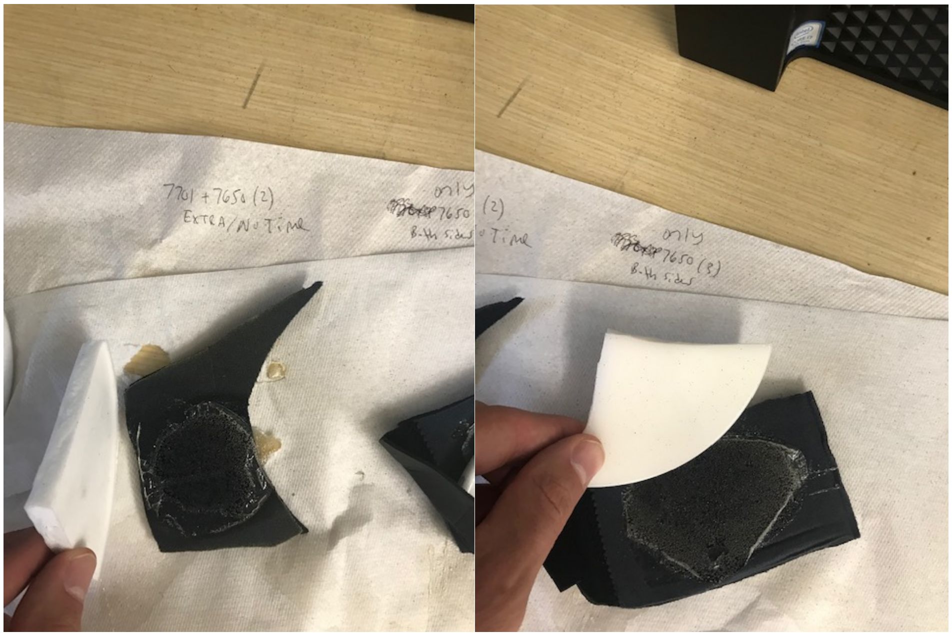

Figure 12. Lord adhesives with neoprene and our composite material.

After multiple failures, we then tested these adhesives on a cured piece of PDMS, as seen in Figure 13, since glass is inert. However, this again resulted in failure with the material only sticking to the neoprene.

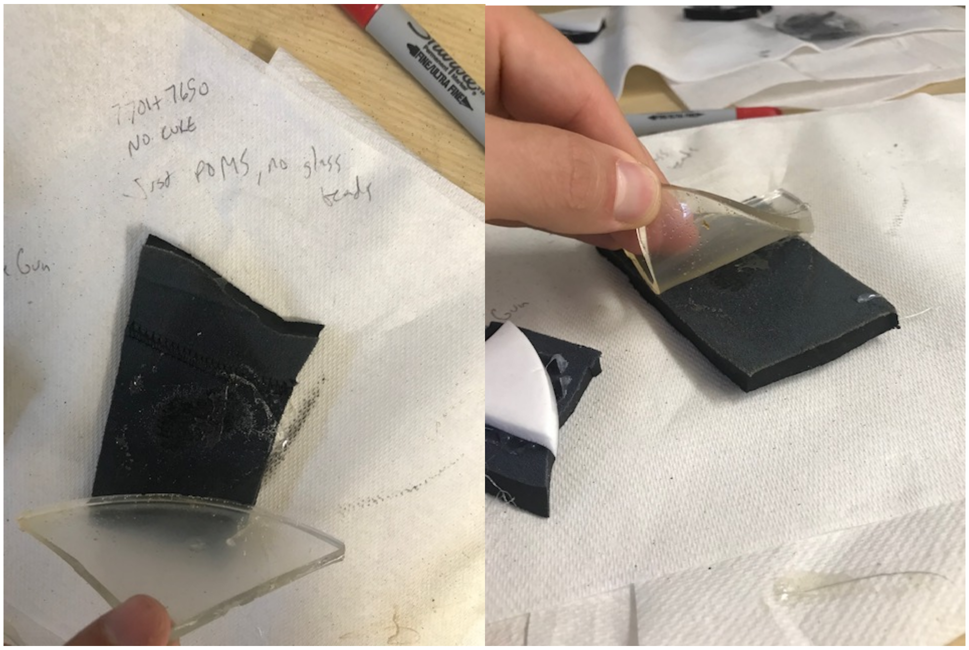

Figure 13. Lord adhesive with neoprene and PDMS.

4. Spray Paint

Finally, we attempted spray-painting the composite pieces as a coat before using some of our previous ideas for adhesives. However, before we could experiment with the other materials, we tested the composite with the dried spray paint, and the paint cracked apart very easily. At this point, it seemed that nothing would stick to the composite.

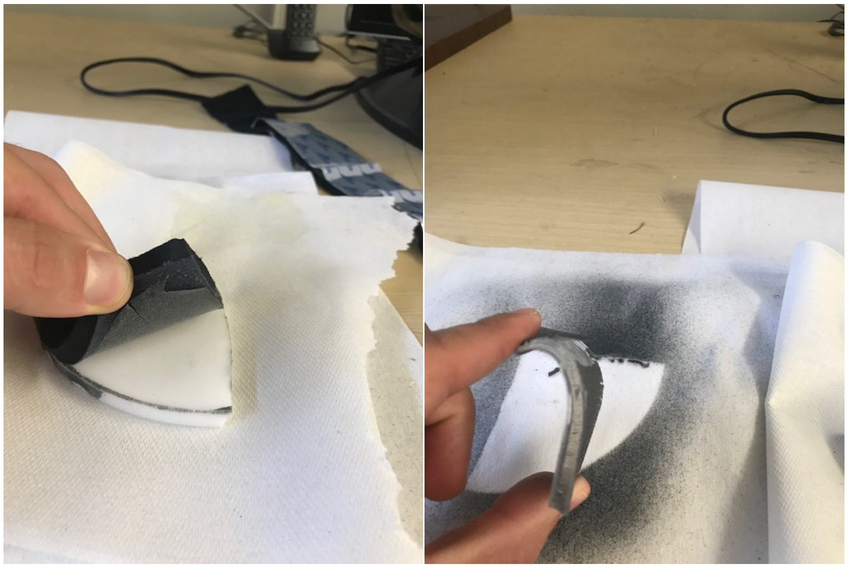

Figure 14. Spray-painted composite not adhering to the composite.

B. TEMPORARY SOLUTION

Given that this was a prototype and not a final product, we only needed to be able to test the ergonomics of the piece and ensure the user can perform various functions, mainly swimming. We began testing by placing the composite piece in between the neoprene wetsuit and human skin. This worked well enough to test ergonomics and such was a temporary solution while we continued investigating a mounting solution that worked and can be more permanent.

We also tested this in the water as motions like moving arms in circles and bending forward and backward on land is different than in the water. While in the water, performing swimming strokes of military side stroke and freestyle with the composite material inside the wetsuit was not inhibiting. Therefore, we decided to move forward with testing without an adhesive as we continued to search for a more permanent solution.

C. WETSUIT WITH POCKETS

Finally, we turned to our colleagues to help us with our adhesive problem. A classmate of ours, LT Max Cutchen, suggested a creative solution of adding pockets to the wetsuit and bypass the issue of adhesive altogether. Furthermore, he knew a local company, Otter Bay Wetsuits, that could create the pocketed wetsuit.

I was then measured for a custom-fitted wetsuit by Otter Bay Wetsuits. At the final fitting, we measured the size of the pockets by putting on the wetsuit, placing each piece overtop the wetsuit, and marking the outline for where the pockets will be placed.

Figure 15. Front side of wetsuit with composite pieces inserted into pockets.

The final pockets were not as big as we had intended. The pockets to hold the composite pieces were originally going to be sewn into the wetsuit. This turned out to be very hard for Otter Bay Wetsuits because their sewing machine has a limit to the thickness it can access, and putting multiple layers on made it too much for that machine. So, we took the alternative solution and glued the pockets on. This took more room than a simple stitch would have, and Otter Bay Wetsuits did not expand the pockets by the glue margin, or consult us about it before moving forward. The pockets were also too close to each other in certain places, which then resulted in trimmed down pockets. This resulted in us having to cut off a significant portion of each composite piece, reducing our body coverage to about 50%. This was not ideal, but since this was our first prototype wetsuit, Mk1, it could only be improved. The upside of these struggles was the gained experience that would allow the next version of the wetsuit to be designed and built more efficiently, effectively, and simply. In addition, the resulting Mk1 wetsuit was good enough to begin field testing.

III. TESTING

A. SPEARFISHING TESTS

While we were waiting for the wetsuit to be made, I decided to use my hobbies to help me with my research. The composite pieces we had made had only been tested while wearing a wetsuit in a lab. This involved a quick test of moving my arms and torso around but I needed to actually test it in the water. I spearfish as a hobby and wore the composite pieces out while spearfishing, which was ultimately a success as the composite pieces fit perfectly along the contours of my body. There was very little restriction of movement while I was swimming and diving and swim strokes felt natural. There was a little discomfort but this could be easily fixed with some fine-tune cutting and trimming of the composite piece.

We used my spearfishing as proof of concept tests before starting diving tests. The first time, I only wore a couple of composite pieces to see how it would impede me ergonomically while I was spearfishing, which is an active sport. I swim out to different areas looking for fish, which requires both arm motion for freestyle swimming and flutter kicks with your legs. Reconnaissance needs to be made to be able to see if fish are in the area or not. This requires the diver to take a deep breath and dive downward head first, kicking with their legs in a dolphin kick to propel them to the ocean floor. The hunter is then continuously swimming and looking around rocks and crevices, all the while holding a spear pole ready to strike. Whether a fish is found or not and whether it has been killed or not, the diver still has to surface and regain breath. This action happens multiple times over the hour or two the diver is swimming and hunting. Out of all of these actions happening, the composite pieces did not inhibit any actions while swimming. This was excellent news since it was unknown if these composite pieces were going to be comfortable, and therefore practical for real-world use.

I continued to dive with various composite pieces and added more as we continued to produce them. Swims continued to feel natural while in the water. Since these were all being done while the wetsuit with pockets was being made, it also seemed reasonable to test our temperature and pressure sensor.

After a successful few swims, I began using our OM-CP-PRTEMP1000 Rugged Pressure and Temperature Data Loggers, as shown in Figure 16. These are about six-inches long, one-inch diameter cylinders and are used to record the temperature and pressure. I placed one of these length wise on my sternum and another width wise along the small of my back. I also had a third one that is attached to me on the outside of the wetsuit to be able to get the ambient seawater temperature and pressure.

Figure 16. Two Omega OM-CP-PRTEMP1000 rugged pressure and temperature data loggers.

Although this was only tested once, it clearly showed there was about 3° Fahrenheit difference. This was some positive preliminary news to be able to roughly test the composite pieces and know this was actually able to keep us warmer.

B. DIVING TESTS

Once the wetsuit was completed with the pockets, we wanted to do similar tests to be able to have a like comparison. At this point, Demers had graduated, and LT Ted Kinney graciously volunteered to be my dive partner for these experiments. We planned two dives that are the same route, once with the composite pieces and once without. This was done so we could have similar tests to ensure we were comparing like tests. As this was not done in a lab, there were multiple variables that could affect the results but are likely minor. For instance, there could be a slight change in water temperature from day to day due to the change in tides and currents. Bottom time can also change due to how much oxygen the diver is breathing. If they are exerting more energy, they will consume more oxygen. These were all small variables that we believed would not skew our results but actually provided more real data from field-testing that was needed instead of near-perfect lab-controlled results.

We also wanted to make sure that the wetsuits were similar when we performed these tests with and without our composite pieces. Two different ideas were originally thought of when we began our tests. Firstly, we thought to compare the same wetsuit that was built with pockets for our composite pieces to be compared with and without the composite pieces. This gave us a similar comparison when taking tests but was not quite as practical since the wetsuit with pockets is four mm thick. We decided on four mm due to the fact that the composite pieces add another five mm thick. The advantage of a four mm thick wetsuit is that we have more flexibility than the thicker eight mm. We wanted to highlight the fact that we could have a thinner neoprene wetsuit for more flexibility and then use the composite pieces for thermal insulation.

Secondly, we thought to compare the new wetsuit with composite pieces with a regular eight mm neoprene wetsuit, as this is the common practice around the world for cold water dives. This has the benefit of being more practical to the diver in particular but less so scientifically since it would not be a direct comparison.

1. Experiment 1 12JUL2020

The first diving experiment was a good start to learn what went wrong and what could be improved over two dives. The first dive, the waves made getting out a little difficult so the actual dive was only about 15 min at a depth of 25 feet due to the fact that we used a lot of air just getting out there. With the strong current, even at a depth of 25 feet, it was still moving us around a considerable amount. Based on the difficulty, we decided we needed to move to a new spot to collect some better data. The trip back to the beach was also tiring due to the strong current and large waves and really wore us out.

Figure 17. First dive with composite pieces in place.

For the second dive, we went to a cove and the dive was much better. The current was almost negligible which allowed us to be able to dive freely without having to fight the current and there were no waves. This dive lasted around 45 minutes but we could not keep a constant depth due to adjusting to the natural unevenness of the sea floor. This was a good lesson to learn going forward to always check the depth and try as much as possible to keep a constant depth.

We came to several conclusions after swimming with a full wetsuit with all the composite pieces in. First, the lower back piece had to be cut into two pieces to fit the pockets but this did not work practically. One piece fell out and was lost at sea and the other one easily fell out back on land, so I kept the second piece out for the second dive. Rather than use the pockets for the back composite piece, I put them inside the wetsuit itself as I had originally tested it. I also noticed during the dive that my semitendinosus was hurting, resulting from the fact that we did not make exact molds for the hamstring. To correct this completely, I would have to make a new mold. I also noticed that the back hamstring piece could not be too long as it would start to rub on the semitendinosus. As an immediate fix, I shortened the hamstring composite piece so as to prevent this from happening again. The abdomen piece also fell out at one point so I would also place this piece inside the wetsuit rather than using the pockets in the future.

While I was cleaning the wetsuit and taking out composite pieces, I noticed that some of the composite pieces broke while out diving. This could be from a multitude of sources including the actual removal of the wetsuit. This tends to be a tedious process and can require a second person to help because the composite pieces bulk up the wetsuit and the calf, hamstring, and quad composite pieces get caught on each other when the wetsuit is being pulled off. This could be improved by using a polymer that has greater elasticity.

I specifically noticed that one of the calve composite pieces and one of the hamstring composite pieces were broken. This has also brought about thoughts of possibly using a polymer with a greater elasticity, as it would result in less breakage. This could lead to a possibility of an entire wetsuit lined with our material or the possibility of making a wetsuit of something entirely new. For the purpose of testing, I simply used the mold to recreate the broken composite pieces.

Since this was the first test, there were a lot of learning curves to overcome but it taught us a lot. Every experiment going forward was improved as new ideas on how to test came up. Two ideas were brought up after this first dive: try to dive once with composite pieces and once without, and the other would be for my diving partner to wear a thinner wetsuit that was comparable to what I was wearing. Both ideas were explored in the next experiment.

2. Experiment 2 19JUL2020

The second test was much more productive than the first and I was able to implement fixes from what we learned in the first dive. For this dive, I dove with my wetsuit with pockets without the composite pieces. This was done so as to have a baseline and see if the wetsuit with the composite pieces inserted would be warmer for the next dive. I also had my diving partner wear a similar wetsuit to me. We each had a temperature/pressure sensor on our sternum and a second placed in a free-flow pouch on our BCD's. This way we could measure the difference between our temperature and the ambient seawater temperature. I also shortened the hamstring composite pieces for the back of the leg to be able to have a full range of motion with the bending of my knee and alleviating the strain I had on my semitendinosus, which was successful. For future designs, I determined that the hamstring composite pieces should reach from the gluteus maximus to midway down the hamstring as the way to cover the back of the leg for optimum comfort and range of motion. I also focused this dive on a more constant depth of between 15–25 feet. In experiment one, there were more inconsistencies with the depth with constant rising and diving from the previous dive.

Figure 18. The author and his diving partner, Kinney, before a test dive.

The next dive was conducted with my wetsuit again with the composite pieces in the pockets so as to compare experiment two with experiment three and get an accurate comparison.

3. Experiment 3 26JUL2020

For this experiment, we used the same wetsuits as in experiment two. For my wetsuit, I placed the composite pieces into my pockets, unlike the last experiment. This was done so I could have a comparison of the wetsuit with the composite pieces and without. This proved to be key to the data.

The dive itself was very smooth. Learning from previous experiments, I continued to stay at a constant depth of 20–30 feet. We ultimately discovered that the composite pieces did not retain heat as well as just the wetsuit from the previous experiment, which will be discussed further later in the chapter. This was likely the result of one of three possibilities. The first was that the dive occurred two hours earlier than the previous experiment which could have affected the temperature. However, large bodies of water like the Monterey Bay do not warm up in a single day and my skin temperature would not be affected by the two-hour difference either, which lessens the possibility of time being a factor. The second factor would be depth as I was slightly deeper than the previous week, but only by a mere five to ten feet which would not result in such a drastic temperature change either. This leaves the final factor of the constant water flow into and out of the wetsuit.

When water is continuously flowing into and out of the wetsuit, it constantly drains heat from the warmer body, the human, to the colder body, the water. As described above, this thin layer of water that retains your heat helps insulate you, but when a new wave of water, which is cold, reenters the wetsuit, this causes you to give more of our heat to the new water to warm it up again. We believe this process was helped by the myriad of pockets that are contained all over the wetsuit. With the pockets containing the composite pieces that are open to the sea, we figure this was not actually able to retain any heat due to the fact water is constantly flowing into and out of the pockets, just like inside the wetsuit. As a result, we decided to seal the pockets up and keep the composite pieces inside permanently. By sealing composite pieces in, they were now a part of the wetsuit and also waterproof. Now, we will see if the composite pieces being sealed improve upon retaining heat since this is an extra layer placed on top of the wetsuit, sealed in with no cold water to steal away heat.

4. Experiments 4 and 5, 14 and 15AUG20

To seal the composite pieces in, I took the composite pieces and trimmed them up so that they would be able to fit into the pockets on the wetsuit after it is sealed. I then took the wetsuit back to Otter Bay Wetsuits and they were able to seal the top of the pockets with glue. This was a very quick process. Once the wetsuit was returned, I was ready to conduct my last experiments.

Figure 19. Final dive wetsuit, Mk1, with composite pieces sealed in the pockets.

My last experiments turned out really well for both diving and data collections. At this point in the experiments, the flow and set up of how to conduct the experiments were quite refined. The experiment four dive ended up being an hour and at a consistent depth of 20–30 feet, very similar to experiment three. One of the things we were interested in was whether the ergonomics of the wetsuit would change at all with all of the pockets now sealed. I am happy to report that I retained full mobility and range of motion while wearing the wetsuit. One thought was that because the composite pieces were now sealed in the pockets, it would be too tight and would inhibit mobility. I still believe our four mm wetsuit with our thicker composite pieces covering our vital spots has more mobility than a standard seven mm wetsuit. This dive went extremely well and showed that our sealed composite pieces wetsuit thermally insulated the diver better than a standard three mm wetsuit.

I had originally decided to end experiments with experiment four with how well those results were, but I ended up diving the next day as well and decided to take another set of data. Experiment five was the same as before, except my dive partner was wearing his seven mm wetsuit instead of his three mm. This wasn't exactly planned, but since I just had conclusive data of the composite pieces sealed within the wetsuit being warmer than a three mm wetsuit, this could show how the composite pieces sealed within the wetsuit sizes up to a seven mm wetsuit. We ended up doing roughly the same dive again, staying at a consistent depth of 20–30 feet. At the end of the dive, when the data was collected, the composite pieces sealed within the wetsuit was more thermally-insulating than the seven mm wetsuit. This was great news!

IV. RESULTS AND ANALYSIS

A. DIVING RESULTS

Before each experiment, we took measurements. This was done using the Omega OM-CP-PRTEMP1000 which is a Rugged Pressure and Temperature Data Logger and the Omega Data Logger Software Version 4.2.11.1. This logger can be placed in water up to a depth of 230 feet. These loggers have worked extremely well in recording the data we need to improve wetsuits.

Setting up each logger was relatively simple. We opened the logger with a 9/16 inches' wrench and plugged it into our computer and opened up the Omega Data Logger Software. After this, the software program recognizes the logger, which were all serialized, and I selected quick start. This starts the data recorder which is taking data every 30 seconds. This allows data to be taken for over five days and 12 hours. There is the possibility of having a custom start and stop, but I have found that dives do not always go as planned. They often do not start or end as planned and things often break. Therefore, if I quick start the logger the night before, I know it will be good for the next five days to be able to log data. I am also able to narrow my window of the data I want to examine more closely. Figure 20 shows the Omega Data Logger Software with some uploaded data.

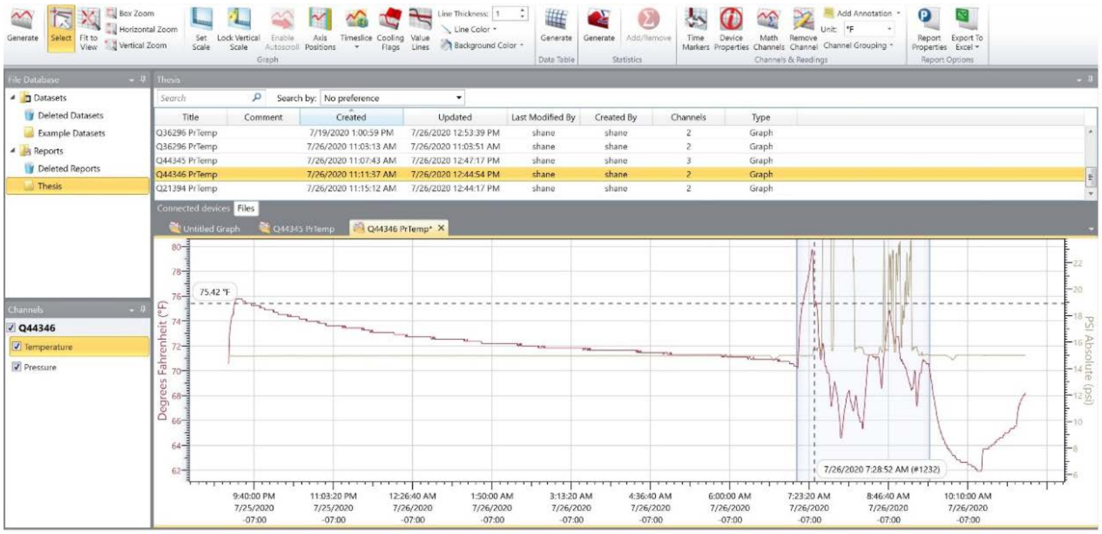

Figure 20. Raw data taken from OM-CP-PRETEMP1000 logger on the Omega Data Logger Software.

After the dive, I plugged the logger back into the computer and simply stopped the device and then uploaded the data recorded for all four of the loggers. Once the data was uploaded, I changed the units for temperature from Celsius to Fahrenheit and narrowed the data from everything collected to the time that I actually was diving, as this is the only actual data needed to make comparisons. The pressure logger helps track exactly when diving begins and ends and how deep we end up going. From here, I export the data out to Microsoft Excel to be able to work with the data better than what is given in the software.

1. How to Measure

Once data was collected, we had to figure out how to represent that data. One option was to plot the temperature traces over time for both the inside and outside of the wetsuit for each case. This would prove very simple and the software product already does this. However, there was no quantitative comparison between the two, just a visual comparison which could easily be skewed with axes or size of the graph.

Another option was to plot the inside temperature in units of the outside temperature. This would give us half the amount of data to plot and it would be very simple.

However, the outside temperature could change between experiments which would affect the fairness of the comparison.

We also considered using percentiles, where we plot the inside temperature as a percentile of normal core temperature. This would be the most relevant of our ideas of representation, but there is no good way to show ambient temperature, which again will change between experiments, and therefore we also dismissed this measurement option.

We ultimately measured our data by finding the delta of the temperature. As shown in Equation 1, we subtracted the outside temperature from the inside temperature in order to find the difference.

$$\Delta T = T_{inside} - T_{outside} \qquad (1)$$

We felt this was a good representation of the data and would be easy and clear to understand visually.

2. Data- Experiment 1

The first experiment showed us how we could improve our system of taking measurements and how things could go wrong. However, just because things went wrong does not render our data irrelevant. Figures 21 and 22 show the deltas from the first experiment. The temperature difference between the front of the wetsuit and the back is almost a full eight degrees. This shows that the back of the wetsuit had saltwater coming in and taking body heat more than the front chest area.

Since this was the first experiment, we learned a lot. The jump in delta temperature occurred at around the one-hour and the three-hour mark when each of the dives occurred. It also demonstrated that the inside of the wetsuit was already cold from the first dive in repetitive dives. Since the inside of the wetsuit was already wet, this drastically affected how warm the wetsuit was, by about seven degrees with the front and 10 degrees in the back.

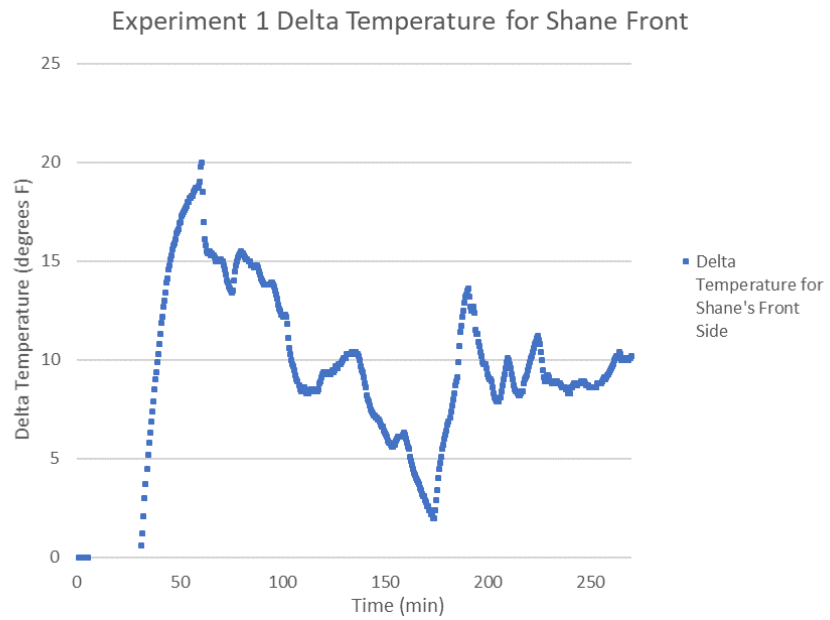

Figure 21. Delta temperature for wetsuit with composite pieces in the first experiment with temperature measured from the sternum.

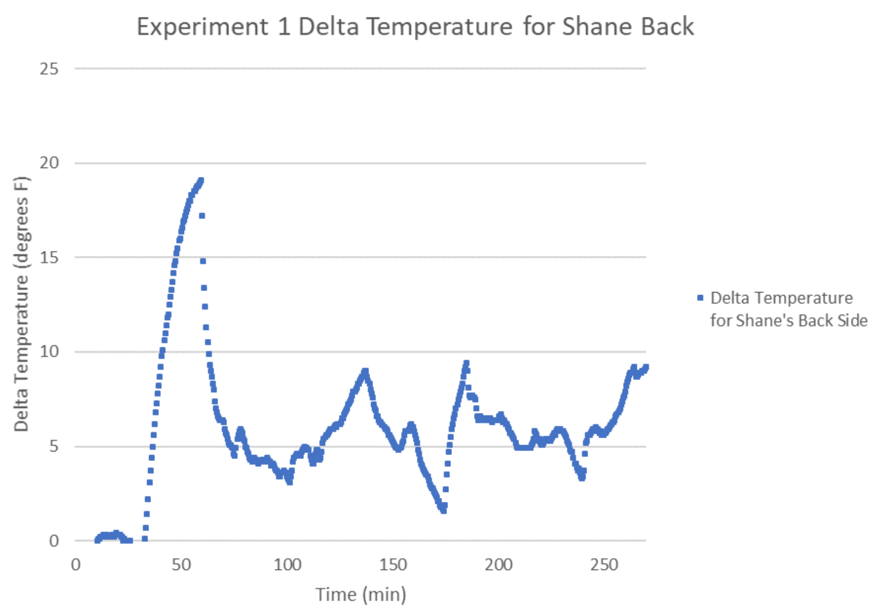

Figure 22. Delta temperature for wetsuit with composite pieces in the first experiment with temperature measured from the lower back.

Overall, this was a successful experiment and led to greater insight on how to conduct future experiments. Firstly, we decided to take the OM-CP-PRETEMP1000 logger from the lower back and instead give it to my dive partner to use as his ambient seawater temperature logger. This was done because when I was wearing my BCD and weight belt, the probe was getting squished between those and my lower back, which is prohibitively uncomfortable even when adjusted. By moving it to my partner, I alleviated my discomfort and gained more ambient seawater data, allowing the experiment to run smoother and more effectively.

3. Data- Experiments 2 and 3

For experiments two and three, each person wore two OM-CP-PRETEMP1000 loggers, one in the torso and one for the ambient seawater temperature placed in an open flow pouch in our BCD. Both divers also wore wetsuits with similar thickness in order to compare delta temperatures. My dive partner wore a three mm wetsuit and I wore a four mm wetsuit with one mm pockets. We found in the first experiment that when my dive partner was wearing a thick seven mm wetsuit, the composite pieces within the wetsuit did not fairly compare at all.

Experiments two and three resulted in data that was very interesting. In experiment two, while I was not wearing the composite pieces, I had a very high average temperature of 22 degrees above seawater temperature compared to having only 13 degrees above seawater temperature when I had the composite pieces in during experiment three, as shown in Figures 23 and 24. This was not consistent with our hypothesis and led to some analysis of why this happened. The dives were similar to each other in depth and time underwater. There was, however, a great amount of water inside the pockets with the composite pieces, which nullified the point of the composite pieces by removing their ability to retain any heat with water continually coming in and out of the pockets.

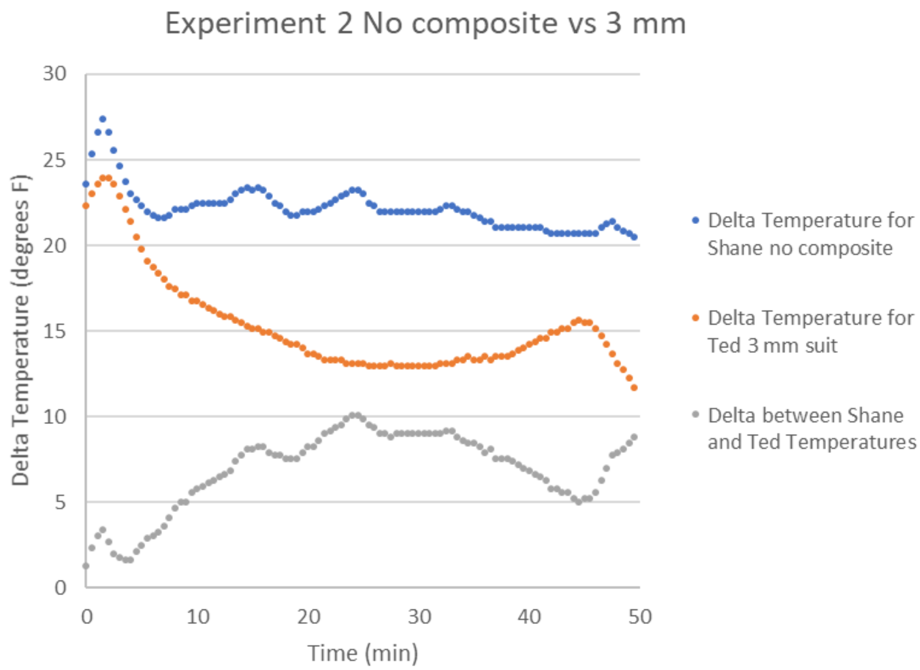

Figure 23. Experiment two delta temperature with no composite pieces. Used to establish a base temperature.

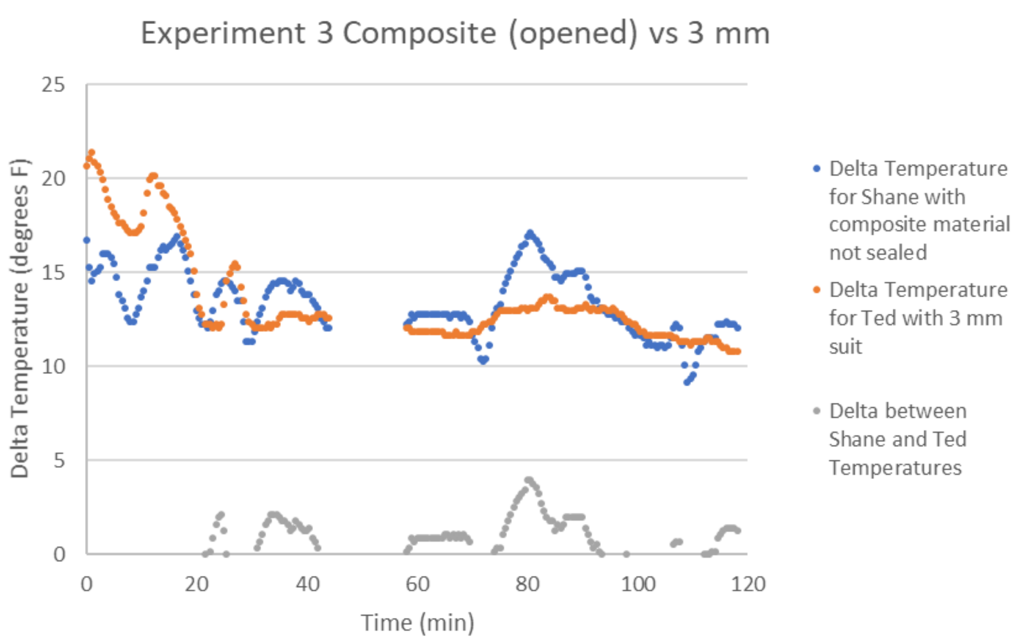

Figure 24. Experiment three delta temperature with composite pieces inside the pockets. The blank space was time out of the water.

Since experiment two and onwards we had a good data set to do comparisons for, we changed the way in how our graphs were presented. We kept the delta temperature for myself and added a separate delta for my dive partner Ted. We then subtracted my delta from Ted's delta to show exactly how much better or worse our custom-made wetsuit is, compared to a standard wetsuit. As we can see, this data collected showed that a wetsuit with no composite pieces is warmer than with the composite pieces, which was not what we had predicted. I also observed a lot of water was flowing in and out of the pockets, rendering the composite pieces ineffective, leading us to seal our composite pieces into the wetsuit to accomplish a higher thermal insulance.

4. Data- Experiments 4 and 5

As with life, sometimes the best things happen last. My last two experiments showed that our wetsuit with the composite pieces sealed in was warmer than experiment three, the three mm wetsuit, and the seven mm wetsuit. In experiment four, which can be seen in Figure 25, I am on average 2.57 °F warmer. The next day during experiment five, I was 5.8 °F warmer, as shown in Figure 27. This was much better compared to experiment three when I was actually 0.14 °F colder on average. Figure 26 shows our diving depth for experiment four. The fact that I was at a deeper depth than my diving partner, and I was still warmer than him, proves that there would have been an even greater temperature delta due to the shrinking of his neoprene wetsuit. In Figure 28, we were closer in depth, which I believe is why I had a greater delta temperature than my diving partner. Further tests with more closely monitored depths would help improve and solidify our data conclusions. It could also be seen that in both experiments, the temperatures started to taper off. Experiment four, with the three mm wetsuit, tapered off around 3 °F whereas experiment five tapered off about 7 °F. Examining the taper off delta temperature could be seen as a slightly better comparison to the average delta temperature due to the fact that both of us were losing heat rapidly at the beginning and there was a point that we start to level out at.

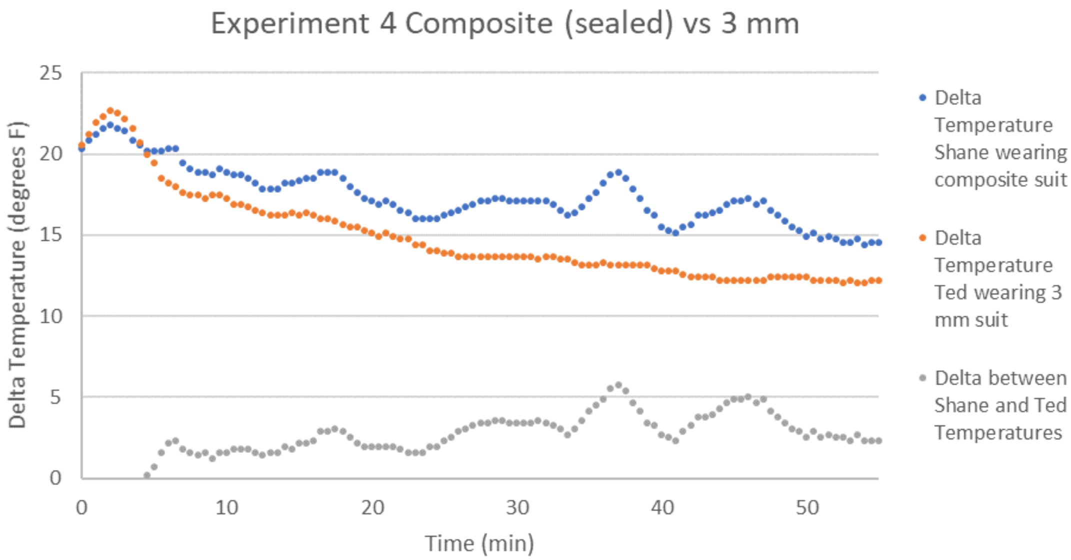

Figure 25. Experiment four delta temperatures with the composite pieces sealed in against a three mm wetsuit.

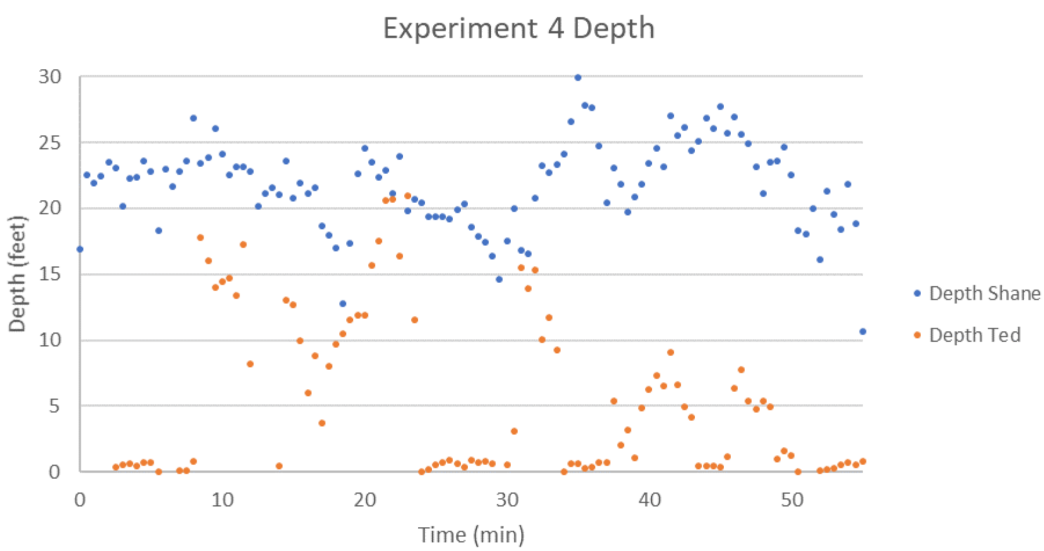

Figure 26. Experiment four diving depth.

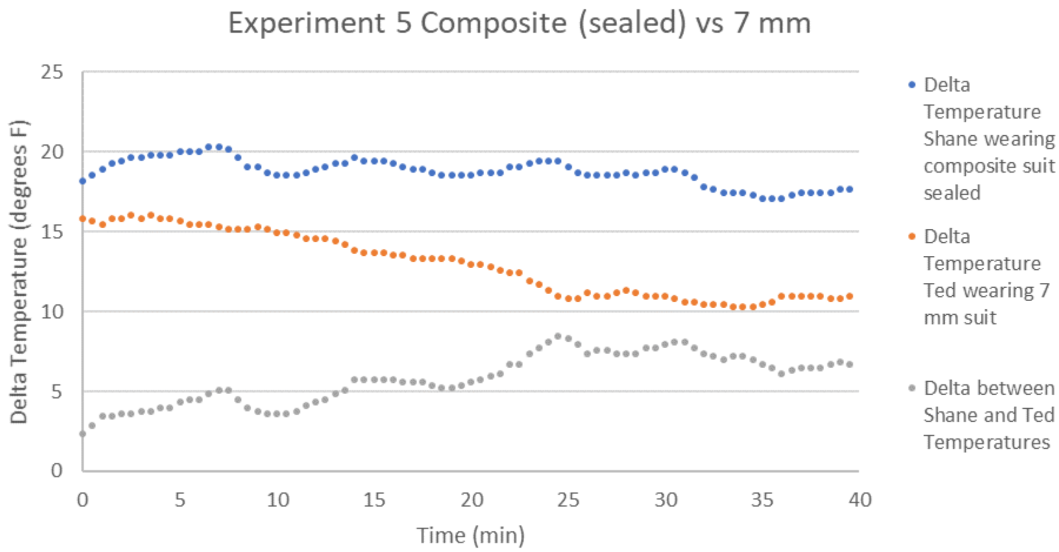

Figure 27. Experiment five delta temperatures with the composite pieces sealed in against a seven mm wetsuit.

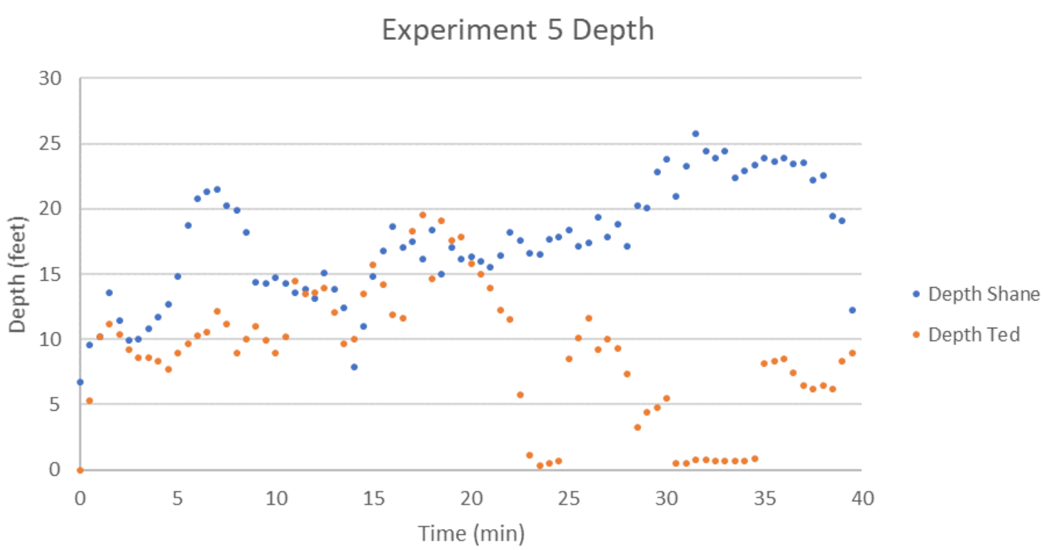

Figure 28. Experiment five diving depth.

Our field data is valid but still very preliminary. We have shown that our composite pieces work, our approach is correct, and manufacturing composite pieces and measurement techniques are appropriate as well. However, we still have more optimization to do. This could be the pockets, and therefore the composite pieces, covering more area, continuing to improve the segmentation, and finishing up the rest of the body, mainly the head and arms.

B. DID IT WORK TO WHAT WE THINK?

After conducting experiments four and five, it can be concluded that our composite material increases thermal insulance. I think improvements and more experiments could be done to continue to look at all aspects of heat loss while diving.

Other ideas to look at are metabolism rates. Since there are two divers, each will have their own metabolism rate, body composition, and diet that will affect heat output. Certain foods are known to slow down the metabolism, while others speed it up. To take it a step further would be to try to eliminate these variations. One way is to take each other's temperature as if looking for a fever just before donning the wetsuits. If both temperatures are normal, then that factor is accounted for. To account for metabolic differences, one could go as far as having the same breakfast as the other. Caffeine and prescription medication also have metabolic effects. Caffeine has been proven to increase metabolism [12]. It would be interesting to see if a cup of coffee would make a thermal difference we could measure, but it is something that can be looked into.

1. Potential Immediate Uses

Some immediate uses that this could be used for would be divers in cold water now. By simply adding pockets to their current wetsuit, casting composite pieces and inserting them in, and then sealing the pockets, divers would be warmer. This is also a good way to be able to start getting feedback from divers around the world on what is working and what is not working. All human bodies are similar and symmetrical so the prototype casts that we have could easily be enlarged or shrunk depending on a person's size. The work so far seems very promising in terms of ergonomics, manufacturing, thermal properties, practicality, and cost.

2. Potential Modes of Use

Some of the modes of use to build the composite pieces for the wetsuit could be having a database of sizes for each composite piece being made. This would be cheaper than scanning every diver for custom made composite pieces. By having sizes of XS, S, M, L, and XL, this would cover the vast majority of divers. This would also take care of body proportion variability, so I can have a large size for the chest but small size for legs. A small loss in efficiency would be paid off in decreased cost and complexity. A further compromise on that path is to have one initial size for each piece to be mass produced, but then during the fitting, each piece would be trimmed to the shape of the individual diver, before the marking of the pockets is done. That mode would be even cheaper and simpler to implement and still offer significant benefits in thermal insulation while retaining the mobility of the wetsuit.

C. FUTURE TESTING AND RESEARCH

As with all research, it is never finished. Everything is continually improving, less expensive, easier to use, etc. The same can be said with the experimental wetsuit. The accomplishment of getting the wetsuit completely made and tangible data of how well it works is an achievement in itself. Now, it needs to continue with finishing molds for the rest of the body, a new wetsuit, and looking at ceramics.

1. Complete Wetsuit— Head, Arms, Hands, and Feet

Demers and I were able to create seven molds to be able to cover 70% of the human body with composite pieces. The last 30% will have to go to the head, arms, hands, and feet. The head would be a half sphere to cover the skull starting at right above the ears. Three molds for the arm would be the best: biceps, triceps, and forearm. These three would use the natural muscle contours of the body to be able to make composite pieces. The hands and the feet would pose the biggest challenge. This is due to the fact that the best way to retain heat would be to just make plates for the back of the hand and the top of the foot. Making composite pieces for the digits is something that is going to take precision and more expertise.

2. Better Pockets

The wetsuit we have now, the prototype Mk1, is sufficient for future tests but there will need to be improvements. For instance, the composite pieces could be incorporated better into the wetsuit itself. The pockets were not able to be sewn on so they had to be glued on which cut down on how much the composite pieces were able to cover on the body due to the width of the glue on the material being used. This width minimized the composite pieces able to be placed inside the pocket. If the pockets were able to maximize more of the wetsuit, this would enable maximum amount of coverage with the composite pieces.

Another improvement is to test multiple wetsuits with different thicknesses to see if the composite pieces help all wetsuits or end up hindering some wetsuits. That could help some wetsuits a lot, but others it’s not worth the small amount of help it gives.

3. Different Material-Ceramics

We have also considered changing the composition of the composite pieces from glass beads to ceramic beads. The reasons for this would be two fold. One, it would make the composite pieces heavier which could then relieve the diver of having to wear a weight belt. Ceramic is also less likely to break during the mixing cycle than glass which improves the overall effectiveness of the material. Most importantly, ceramics have significantly lower thermal conductivity than glass. The hollow glass bead conductivity is due to the thin glass shell, so changing the beads to ceramic would improve the insulation significantly. The tradeoff is increased overall weight, but as mentioned above, that will just replace the ballast belt that divers have to use otherwise to cancel the buoyancy from the breathing mixture tanks. A ceramic composite wetsuit may also be somewhat more comfortable to wear, since the weight would be better distributed across the body as opposed to just along the hips with a ballast belt.

4. Increase Elasticity in Composite Pieces

Increasing the flexibility in the composite pieces may also increase the effectiveness of the wetsuit. Turning them around in your hands and bending them, the composite pieces are fairly sturdy and flexible. This changes when put up against any active attempt to rip the composite piece in two, as multiple composite pieces broke while diving during one experiment. A different polymer could be considered that would be able to increase the elasticity of the composite pieces using either glass or ceramic microspheres. This could start the journey to possibly making a wetsuit out of microspheres and polymer vice neoprene. For example, if the breakage mostly happens during the mechanical rigors of donning or undonning the tight wetsuit, an alternative wetsuit entry design might circumvent this problem. I especially noticed the difficulty of undonning the wetsuit due to the multiple composite pieces on the legs. This ended up having to be a two-person operation to take my wetsuit off.

5. Minimize Amount of Water Coming into the Wetsuit

By decreasing the amount of water coming into the wetsuit while diving, we can increase the wetsuit's effectiveness. While diving, water comes into the wetsuit and the body warms it up. The problem that happens is new water enters the wetsuit which requires another exchange of heat. If advances in wetsuits lead to a decrease in water coming into the wetsuit via the wrists, ankles, and neck, heat loss would be decreased. Incorporate this with our composite pieces, the diver is going to retain heat and be able to perform their job. Ultimately, this is a sealing problem rather than a thermal composite problem, but it is related and must be solved.

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V. CONCLUSION

The Mk1 wetsuit with the composite pieces inserted is the future of diving in cold water. This wetsuit will be able to improve the amount of time a diver is able to spend in the water before hypothermia occurs. This will lead to better performances for the job at hand, whether that is repairing a warship, conducting a mission, rescuing a human, the list goes on.

As humans continue to dive, diving improvements will continue to be a high priority. The goal was to improve wetsuits using our composite pieces to enhance current neoprene wetsuits to have a better thermal insulance. The data we collected showed our composite pieces did improve thermal insulance through our initial experiments of real life testing.

Enhancing three mm wetsuits allows the diver to retain the ergonomics advantage over the seven mm wetsuit. Divers should not need to choose between maximum mobility or maximum thermal insulance, which now is given by the three mm and the seven mm wetsuit, respectively. Our composite Mk1 wetsuit does both. The movement at the joints is critical and by being able to have the same flexibility as a three mm wetsuit and the warmth of a seven mm, the Mk1 wetsuit is a major improvement over existing standard wetsuits.

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