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THESIS

**MICROSPHERE-BASED COMPOSITE WETSUIT FOR
INCOMPRESSIBLE PASSIVE THERMAL INSULATION**

by

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PASSIVE THERMAL INSULATION**

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ABSTRACT

This research aims to produce an improved wetsuit designed to insulate divers at low temperatures and increased depths. Military divers currently use 7 mm thick neoprene wetsuits, which lose thermal performance at high depths due to compression of the material. This poses a serious problem to the safety of Navy divers and mission success. An improved wetsuit with better thermal insulation at high depths would improve mission duration, capabilities, and diver safety. Our wetsuit has a 3 mm neoprene base, with composite casts covering the chest, abdomen, back, and thighs, similar to plated armor. The composite material consists of 3M K1 glass microspheres embedded into a Sylgard 184 silicone elastomer. This provides better thermal insulation than the neoprene material and does not contract at increasing depths in the water. It also provides better mobility along the joints. The proof of concept of this design has been explored in previous projects, and the purpose of this research is to complete the suit with forearm, bicep, and shin panels and to gather extensive data comparing the composite wetsuit to 7 mm wetsuits. We use automated data loggers, external and internal to the suits, to collect temperature and pressure data in field tests. Further testing is required to find thermal improvement. Ideally, the final composite wetsuit will increase thermal insulation for the diver, while the thin material around the joints will provide increased mobility for mission success.

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LIST OF ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
3D	three dimensional
ABS	acrylonitrile butadiene styrene
BCD	buoyancy control device
BCE	before common era
Capt.	Captain (Marine Corps)
EDO	Engineering Duty Officer
ENS	Ensign
EOD	explosive ordnance disposal
LT	Lieutenant
m	meter
mm	millimeter
ND	Navy diver
NPS	Naval Postgraduate School
ONR	Office of Naval Research
Pa	Pascal
PADI	professional association of diving instructors
PDMS	polydimethylsiloxane
psi	pounds per square inch
SPEC WAR	special warfare
STL	stereolithography
UWSH	underwater ship husbandry
W/[m*K]	Watts divided by meters-Kelvin

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I. INTRODUCTION

A. BACKGROUND

Although the early history of diving is not well recorded, it is known that ancient civilizations first dove as a means of collecting food. Eventually, diving would evolve into a commercial interest as certain shells, pearls, and corals were sold and traded. Early references of the first breathing apparatus date back to the year 332 BCE, when Aristotle recounted Alexander the Great submerging into the Mediterranean in a diving bell [1]. As these bell-shaped devices were lowered into the water, they would trap air in. With weights and ballast to offset the buoyancy forces of the air, divers would sit inside the diving bell as it descended. Divers used these to breathe, then would swim out of the bell, holding their breath as they located desirable items on the seafloor [1].

While diving remained popular and profitable, it was not until the first air pump was invented in 1650 that the equipment started to dramatically improve. In the coming decades this technology would be incorporated into the first official diving bell patent. This diving bell was the size of a chamber and would use pipes to refill the bell with air from the surface. After another period of stagnation, the first hard hat diver helmets were invented in 1823 [1]. These were originally supported by surface air pumps and used to salvage ancient ships. It was not until 1876 that the first self-contained breathing unit was invented, sparking further interest in the sport [1]. As diving became safer and easier in the 20th century, its recreational, commercial, and military applications grew.

B. MODERN MILITARY APPLICATIONS

The U.S. Navy has recognized the tactical benefits to diving, deploying divers around the world and even creating a Navy diver (ND) rate for enlisted personnel. There are many Navy communities which involve diving, to include the explosive ordnance disposal (EOD), special warfare (SPEC WAR/SEALS), civil engineering corps (SEABEE), diving medical technician (DMT), diving medical officer (DMO), engineering duty officer (EDO), combat camera (COMCAM), and enlisted fleet diver (ND) Communities [2].

Navy divers have a variety of mission sets, to include underwater ship husbandry (UWSH), dive and salvage, and special operations forces (SOF) support [3]. UWSH refers to the repair and maintenance of Navy ships that are in the shipyard or underway by diving down to the hull and performing structural repairs while underwater, usually in the form of welding. The goal of UWSH is to avoid drydocking the ship and maintain operational effectiveness. Dive and salvage missions involve deep dives to the sea floor in order to recover sunken ships and aircraft. This is done to analyze the nature of the incident and recover valuable equipment or technology to prevent others from finding it. UWSH and Dive and salvage mission fall largely under the responsibility of fleet Navy divers and EDOs, who can be attached to shipyards, training commands, or mobile units [2].

The EOD community is responsible for recovering and rendering safe a variety of explosives, to include mines and sunken ordinance. Because of this, every member of the EOD community goes through a nine-week dive school and an underwater ordnance division in EOD school [3]. The SPEC WAR community also uses diving for special reconnaissance and insertion [2].

C. CHALLENGES

While there are many dangers associated with diving, one of the most prominent is hypothermia. Hypothermia occurs in stages depending on the body's core temperature. Normally, it is 98.6° Fahrenheit (F). Generally, when it drops below 96°F, mild hypothermia kicks in with shivering and impaired physical ability. Below 92°F, the mental state is altered, and below 82°F leads to a loss of consciousness [4].

In the United States, an average of 1300 deaths are attributed to hypothermia per year [5]. Hypothermia can be treated relatively easily, but its impairment of mental and physical functions makes it an insidious condition. Divers often push through numbness, feeling cold, and shivering, but this is extremely dangerous. One could roll the dice, but they might lose their life. While most of these deaths occur on land, hypothermia can be more dangerous in the water because water cools the body 24 times faster than air of the same temperature [4]. This is because air has a thermal conductivity of 0.0259 W/[m*K] at 68°F [6], while the thermal conductivity of 68°F seawater is roughly 0.604 W/[m*K],

depending on the salinity and temperature [7]. This thermal conductivity also increases at higher pressures, or increased depths. This is problematic because diving often requires divers to stay underwater for long periods of time, usually at a depth well below the surface. Figure 1 depicts the expected survival time and time before unconsciousness for humans 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 times before unconsciousness and death based on water temperature. Source: [4].

Without thermal protection, diving would not be possible. Fortunately, there are a few ways to minimize heat loss while diving. Wetsuits, dry suits, and atmospheric dive systems have been created to protect divers in recreational, commercial, and military applications. While dry suits and atmospheric dive systems offer better thermal insulation than wetsuits, wetsuits are far more common recreationally and commercially due to cost. Navy divers occasionally use dry suits and atmospheric dive systems for their deepest and coldest missions; however, there are many cases where they do not have this luxury. Navy divers often require higher mobility and dexterity in their operations and therefore use wetsuits.

Wetsuits are designed to allow a small amount of water in through the neck, wrists, and ankles. The body then heats up the small layer of water between the user and the wetsuit, and this small layer of water stays warm around the body. It is important to have

a properly fitting wetsuit because if the openings in the wetsuit allow water to cycle in and out, the body will constantly lose heat to the cool water inside the wetsuit.

As previously mentioned, Navy divers are often forced to use wetsuits due to the requirements of their missions. Divers engaged in UWSH missions need to weld underwater, and EOD personnel need to have the dexterity to disarm mines. On top of this, any sort of tear can completely compromise a dry suit, as water would leak in instantly and put the diver at risk. In particular, SPEC WAR divers need to use wetsuits for nearly all of their missions to stay covert and tactically flexible [8].

One major downside to wetsuits is that nearly all of them are made of neoprene. Neoprene contains a high volume of air, which compresses at higher pressures. As you dive below the surface, the pressure increases, and neoprene wetsuits become thinner due to compression. This causes the wetsuit to lose its thermal protection below the surface. The Office of Naval Research (ONR) estimates that neoprene only provides one-quarter of its surface insulation at a depth of 100 feet [8].

This means that in cold-water operations, Navy divers are at a heightened risk of hypothermia, especially during deeper dives. To help solve this issue, ONR and the Naval Postgraduate School (NPS) have been looking into cold-water wetsuits that are alternatives to the standard neoprene currently used by Navy divers [8].

D. POTENTIAL SOLUTIONS

Capt. John Brown, an NPS graduate in 2018, focused his thesis on the thermal insulation of composite materials. Specifically, he compared the thermal properties of neoprene to composite glass microspheres. To do this, he mixed an elastomer with glass microspheres into rubbery, puck-shaped samples. He chose to use K1 glass microspheres from the company 3M due to their low thermal conductivity of $0.047 \text{ W}/[\text{m}^*\text{K}]$ and high crush strength of 250 psi [9]. These parameters were essential, as the thermal properties of the microspheres and their ability to stay intact at increased depths would dictate the performance of the composite wetsuit.

He applied varying pressures to samples of composite material and neoprene to simulate the compression at depths and found that the composite material was able to keep its thermal insulation up to three times better at deeper depths [10]. His research demonstrated that a wetsuit with this composite material would theoretically be able to improve the thermal insulation for divers, as depicted in Figure 2. He also experimented with the composition and found that a volume of roughly 53% was the maximum volumetric density achievable for the glass microspheres, since they cannot be precisely positioned in the mixture [10].

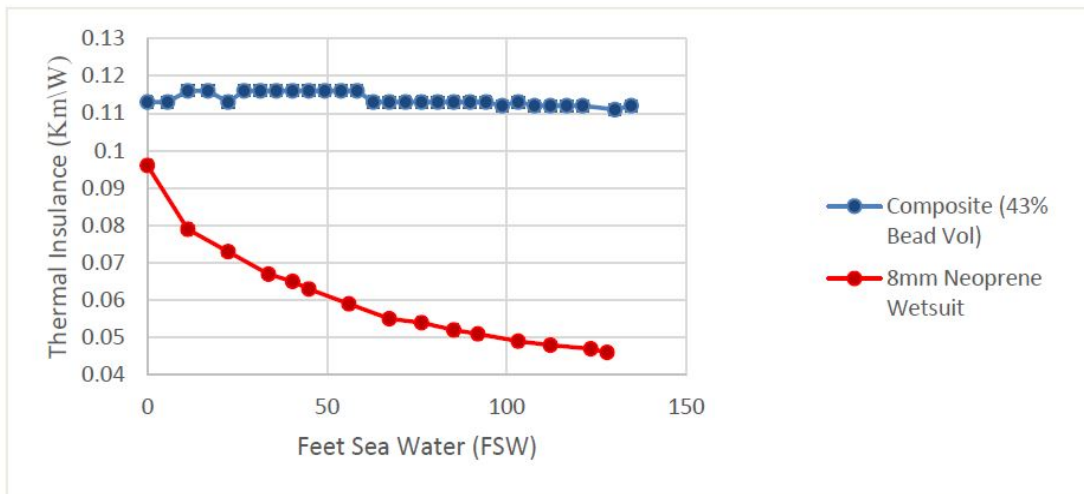


Figure 2. Thermal insulance of the composite material and neoprene as a function of depth. Source: [10].

The following year, Capt. John Brown’s research would be continued to create a prototype of the composite wetsuit. LT Aaron Demers and LT Shane Martin, two NPS students who graduated in 2020, worked to make a Mk 1, or prototype wetsuit. LT Aaron Demers focused his thesis on the research and creation of the suit, while LT Shane Martin focused on the fabrication and testing of the suit’s thermal properties. Together, they were able to 3D print molds and cast a composite material into desired panels. These composite panels consisted of the 3M K1 glass microspheres embedded into a Sylgard 184 silicone elastomer. The panels were then fabricated to fit ergonomically onto a wetsuit.

While LT Martin was able to collect promising data in his last few tests, he noted that further testing would need to be done with a completed wetsuit. This second-generation wetsuit, or Mk 2, would need to cover more of the body to include the forearms, feet, and upper arms. Additionally, more data was required, especially at increased depths. During LT Martin's tests, he never recorded a depth below 30 feet [11]. Data from deeper dives is desired as it will highlight the compression effect researched by Capt. Brown.

II. DESIGNING NEW COMPOSITE PANELS

A. 3D BODY SCANS

To begin the construction of an improved thermal wetsuit, I needed 3D scans of the shins, shoulders, and forearms. LT Shane Martin and LT Aaron Demers captured their 3D body scans for the prototype wetsuit using an Occipital Structure Sensor Mark I [12]. They then used Skanect 3D Scanning software to convert the raw imaging data into mesh files [12]. To create additional molds, I used the 3D scans provided by LT Demers and LT Martin.

B. SCAN PROCESSING IN MESHLAB

Once the 3D scans were processed into mesh files, they could be opened and edited in MeshLab. The body parts that LT Demers and LT Martin worked on included the chest, back, thigh, and ab pieces. In order to maximize the functionality and mobility of the diver, they chose to put the composite pieces over the major muscle groups, leaving the joints free to rotate. This also helped them to insulate more of the body with the composite material, and they were able to cover roughly 72% of the body [11].

In order to continue on the design and further improve the wetsuit, I decided to make molds for the forearms, shoulders, and shins. I also mirrored the mold for the right thigh in order to 3D print a mold for the left thigh. The calf muscles were also considered for molds. Due to the constant extension and contraction of the calves while swimming and the difficulty of putting on the wetsuit, they were ultimately considered infeasible.

The MeshLab scans began as enclosed 3D surfaces of the entire upper or lower body. First, they needed to be trimmed down to the rough shape of the desired body part for each mold. Figure 3 depicts the initial body scan of LT Demers.

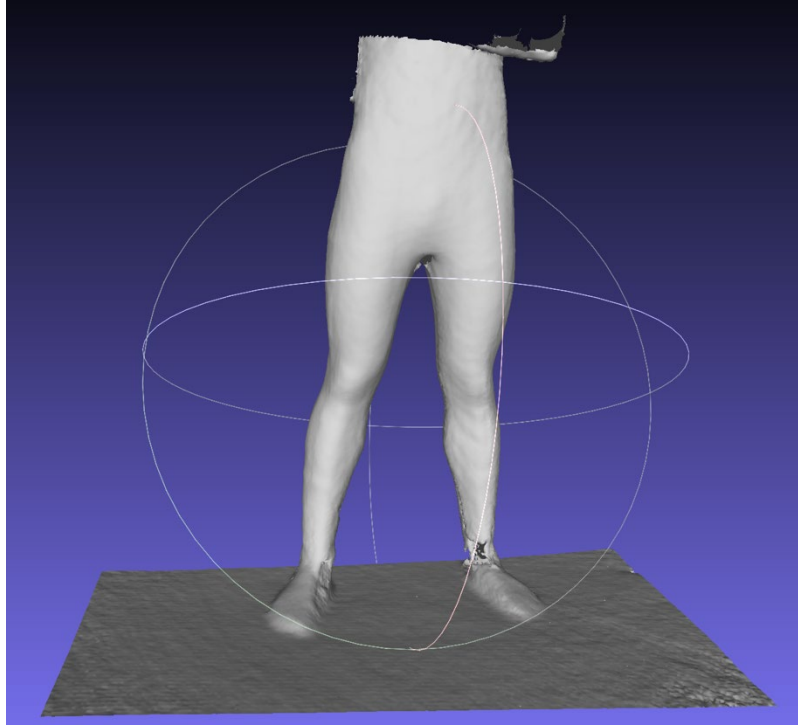


Figure 3. Imported 3D body scan of LT Demers

In order to trim down the scans, the “Select Faces” tool was used and dragged over the surfaces that we wanted to omit. Once selected, I used the “Delete faces, vertices” command. In this case, the desired piece was the shin, so the scan from the feet down was deleted, as well as the everything above the knees. Figure 4 depicts the result of this trimming.

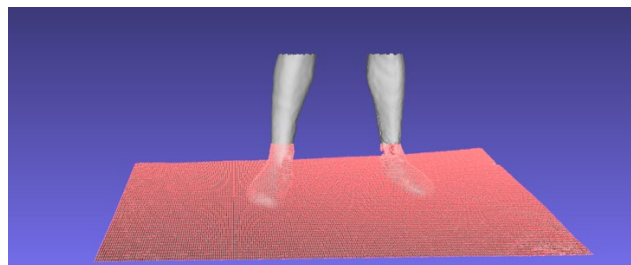


Figure 4. Trimming process for shin piece

Instead of doing the entire process for both sides, I made each mold for one side of the body and mirrored it at the end to create a mold for the opposite side. In this case I kept the left shin and deleted the right side. I used the same process to trim off the backside of the remaining scan in order to have an open surface scan of just the front of the shin. It is important to leave a small buffer area around the desired body part because the scan will be trimmed again with greater precision in SolidWorks.

Once the desired body part was isolated, the file needed to be simplified in order for it to be properly processed in SolidWorks. As it is now, the mesh file consists of a large number of small triangles, called faces, that make up the complex shape that the scan picked up. Many of these faces are so small that they can create sharp edges or intersect with each other causing errors or modeling problems. The sheer number of faces and vertices that make up the scan are also problematic because they can cause SolidWorks to crash or run very slowly.

The first command I used was “Remeshing: Isotropic Explicit Remeshing.” This command reconfigured our meshes to simplify the shape and smooth out any faces that did not align with nearby faces. It did this by collapsing and redefining the triangles in our mesh in order to improve the aspect ratio. This made the body scan much smoother by taking out bumps and ripples, but also greatly reduced the complexity of the shape. Before this command, the scan had over 120,000 vertices and 8,000 faces to define its shape. I was able to reduce it to 1,000 vertices and 1,100 faces with this remeshing tool. The effect of this remeshing can be seen in Figure 5.

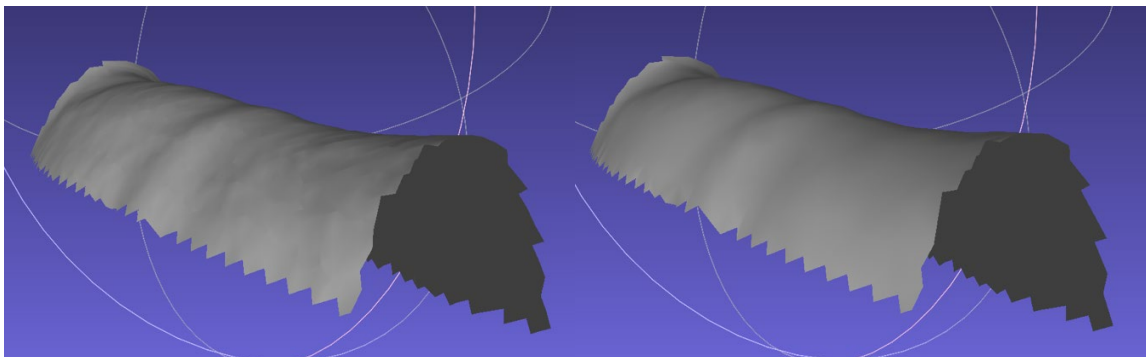


Figure 5. 3D scan of left shin before (left) and after (right) remeshing

While this greatly simplified the scan, I still had jagged edges around the cuts I had made previously. In order to smooth these out and further decrease the number of faces, I used the command “Simplification: Quadratic Edge Decimation.” This reduced the surface to 120 vertices and 200 faces, and significantly smoothed edge along the shin. This simplification of the edges can be seen in Figure 6.

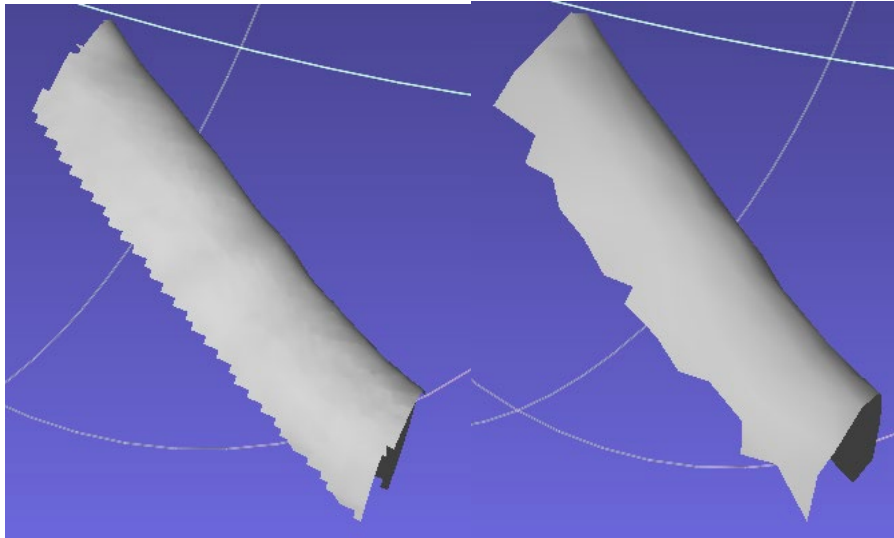


Figure 6. 3D scan of left shin before (left) and after (right) application of simplification

After remeshing and simplifying the scan, it was saved as a STL file so that it could be imported into SolidWorks. Each time a mold for a new body part was made, the scan of the entire body was cut and saved for each individual mold.

C. MOLD CREATION IN SOLIDWORKS

After cutting and processing the 3D image files in MeshLab, I used SolidWorks to create the molds for the pieces. To accomplish this, I needed to make a top and bottom part. These two pieces would need to fit together to make a cavity of the desired shape for the composite panels.

The first step was importing the STL file into SolidWorks. When opening these files, the units of the current SolidWorks project must be consistent, or the scale of the

object will change. This can be checked by using the “Measure” tool once the object is opened in SolidWorks. Figure 7 shows the imported surface in SolidWorks.

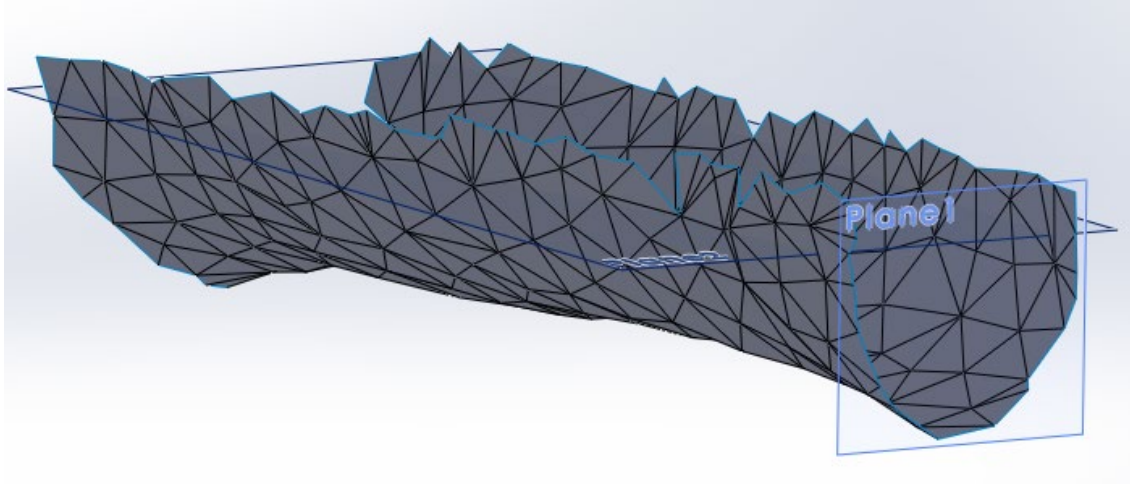


Figure 7. Imported mesh file

The initial cut in MeshLab only allowed the piece to be cut along the lines of the triangles formed. While it produced the general shape of the mold, it needed to be trimmed cleanly to take out the jagged edges. To do this in SolidWorks, I created planes along fixed points on the mold and used the “Surface Trim” command to cut along the planes that were created. Figure 8 depicts the resulting surface.

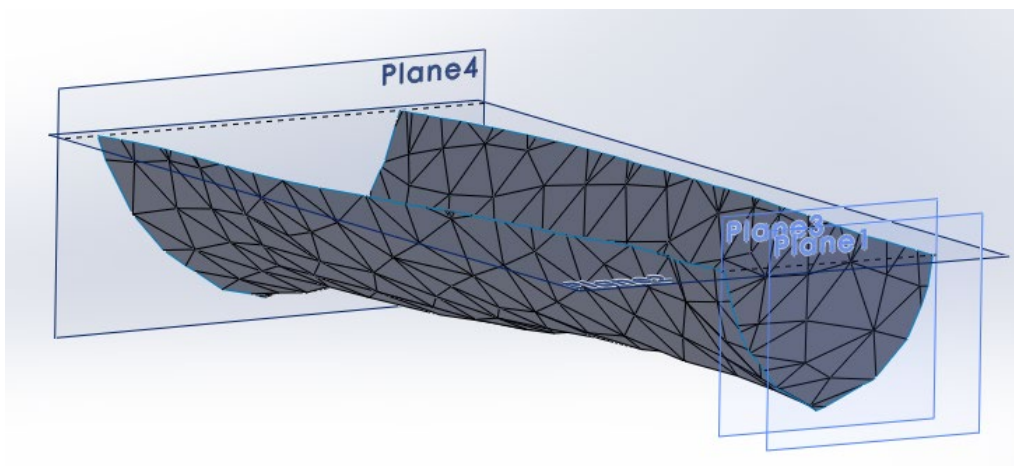


Figure 8. Surface after trim using planes

Once the surface was trimmed, it needed to be thickened to the appropriate size. The desired thickness of the mold was seven millimeters to be comparable to the seven-millimeter wetsuit currently used. To create a symmetric offset for the complex shape, I defined a coordinate system on the apex of the shin. The x-axis was defined as normal to the outward surface of the mold and the y-axis was set in the direction of the foot. In SolidWorks, I used the “Move/Copy” command to create a copy of the surface piece and offset it seven millimeters from the original surface in the direction of the x-axis. Due to the geometry of the piece, the seven-millimeter offset in the x direction made the sides of the surface unevenly offset from the bottom. To compensate for this, I rescaled the outer surface using the “Scale” command. Figure 9 highlights the necessity of rescaling the outer piece, as the two do not line up properly before the rescaling.

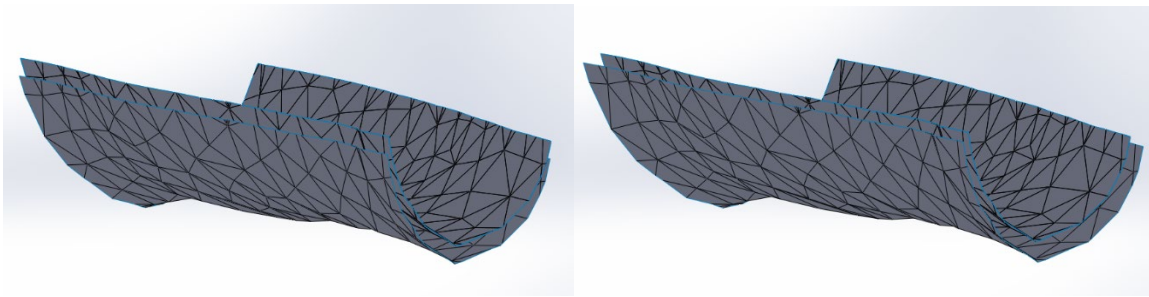


Figure 9. Shin piece and offset before (left) and after (right) scaling of outer surface

After rescaling, the offset became much more uniform and fit the geometry of the inner surface. The rescaling was not uniform since the length along the leg needed to remain the same. I used the coordinate system defined from the initial “Move/Copy” command as a reference for the rescaling, since it already had the desired axial directions. In the “Scale” command, the piece was expanded to 1.1 times its length in the x and z axes and remained the same in the y axis.

Next, I used the “Surface Loft” command to extend another surface between the two adjacent surfaces. This closed the gap between the two initial surfaces but did not create a solid body. During the creation of the lofted surface, it is important to choose

reference points on the two surfaces that correspond with each other. If the reference points are not in the same spot of the respective surface, the lofted surface will become twisted.

The result of the “Surface Loft” is that there are now three surfaces, the two adjacent and the one connecting them. To create one solid body out of these three surfaces, I used the command “Surface Knit” and selected the three surfaces. This resulting solid body can be seen in Figure 10. When using “Surface Knit” it is important to check the boxes “Create Solid” and “Merge Entities” for the desired solid body.

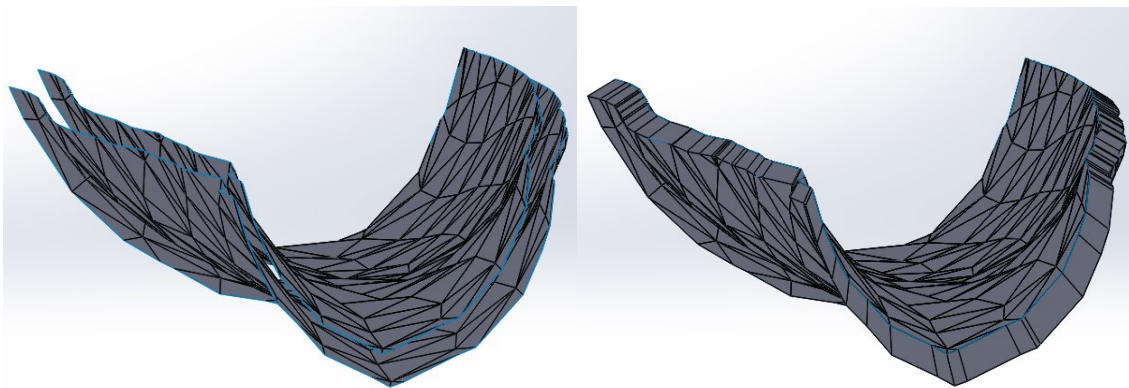


Figure 10. Adjacent surfaces (left) and the solid body created from the surface loft and surface knit (right)

This produced the desired composite piece to attach to the wetsuit. In order to make the mold for this, I needed to 3D print a top piece and bottom piece that come together and form this shape as a cavity. The first step was to go back in the file history to just after the imported surface was trimmed. I created another copy of the first surface, this time keeping it in its original position. This copy will be used to construct the top piece of the mold.

Next, I created a sketch on plane 2, which is depicted as the horizontal plane on Figure 7. From a viewpoint normal to plane 2, I traced the outline of the piece using the “Point” and “Line” features. This is shown in Figure 11.

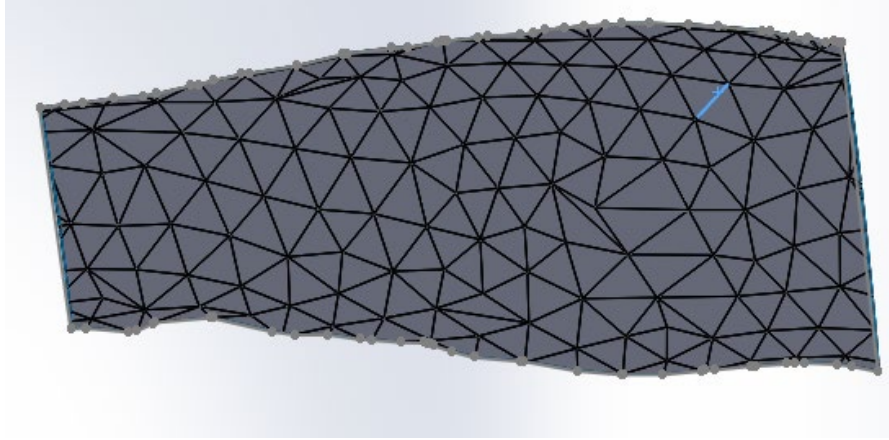


Figure 11. Sketch tracing the outer piece

From this sketch, I used the “Planar Surface” command to create a flat surface of the closed shape that had been drawn. The surface was then offset five millimeters from the plane using the “Move/Copy” command. The copy of the original surface and the planar surface were then filled in using the “Surface Loft” command. The purpose of this copy was to keep these two solid pieces separate. I then used “Surface Knit” with the same settings to create a solid body out of the three surfaces, as shown in Figure 12.

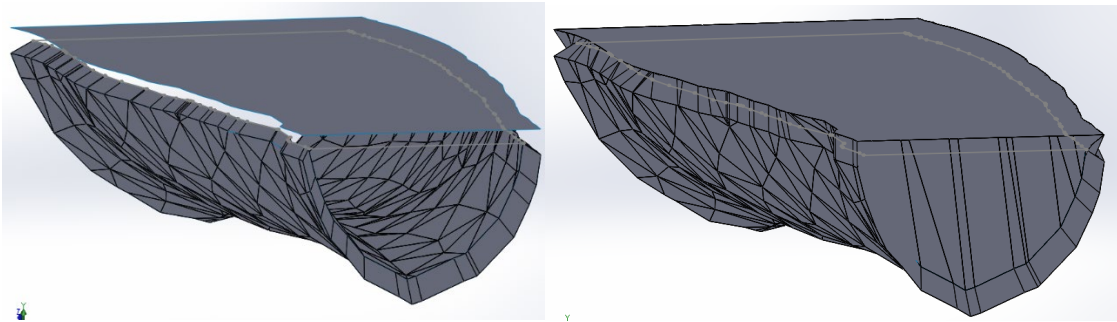


Figure 12. Solid body before (left) and after (right) surface loft and knit

Using the same reference plane used for the planar surface, I sketched a rectangle and used the “Extrude” command to create a box. The extrusion was 100 millimeters in the direction of the mold, with the “Blind” feature on. The resulting extruded box is depicted in Figure 13, as well as the mold piece inside of it.

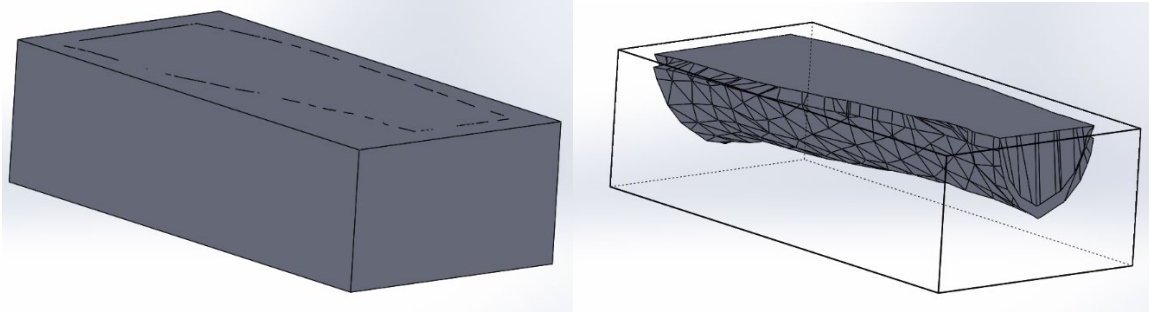


Figure 13. Extruded box with mold piece inside of it, with the box opaque (left) and transparent (right)

The next step was to cut the solid mold piece shown above out of the box. I did this using the “Combine” command. With the two solids inside the box, I selected the extruded box as the main body, the two solids as bodies to combine, and selected the “Subtract” option for the operation type. The resulting mold is depicted in Figure 14.

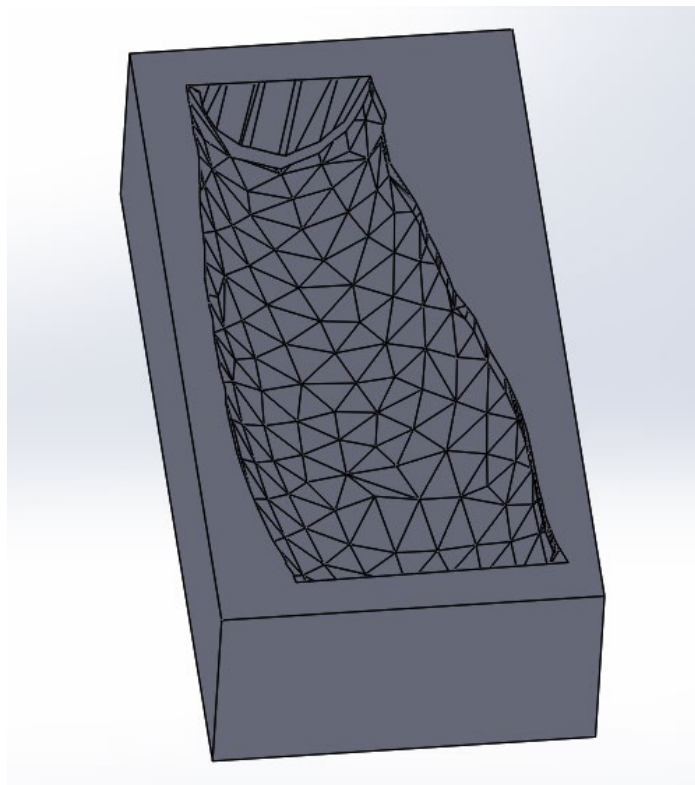


Figure 14. Finished bottom mold

The bottom piece was then scaled up to 1.04 of its original size in order to create small gaps between it and the top piece. If it was not scaled up, then the top and bottom pieces will be the exact same size and will not be able to slide in and out freely.

The top piece was then made using the piece from Figure 12. A new file was created with this part imported. It is important not to include the solid body from Figure 10, as that is the desired cavity between the top and bottom pieces. First, I created a reference plane along the smooth face of the solid. This can be seen in Figure 15.

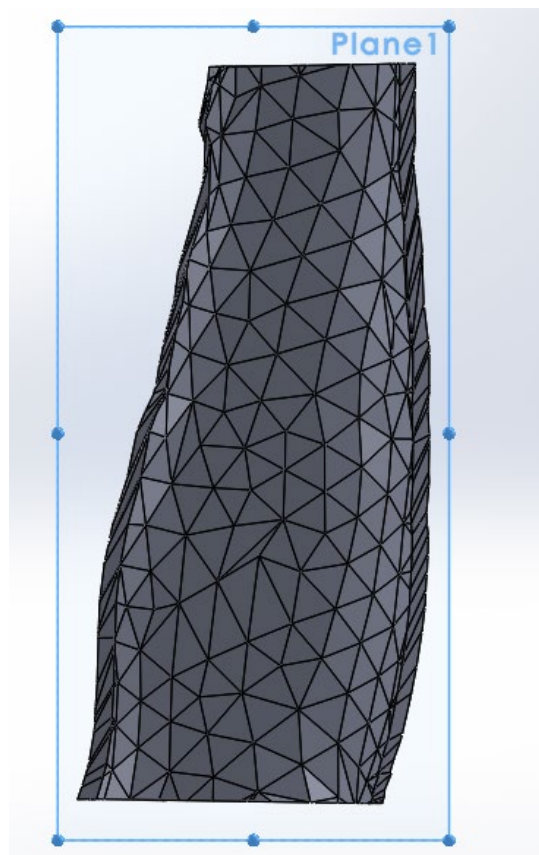


Figure 15. Top piece imported with reference plane

Then I created a sketch along that reference plane, drawing a rectangle and using the “Extrude” command and setting the distance to twenty millimeters in the opposite direction from the mold. This box would act as a handle and allow us to pry the mold open

once it is cast. Then, I used the “Combine” command to merge the two solid bodies into one, as shown in Figure 16.

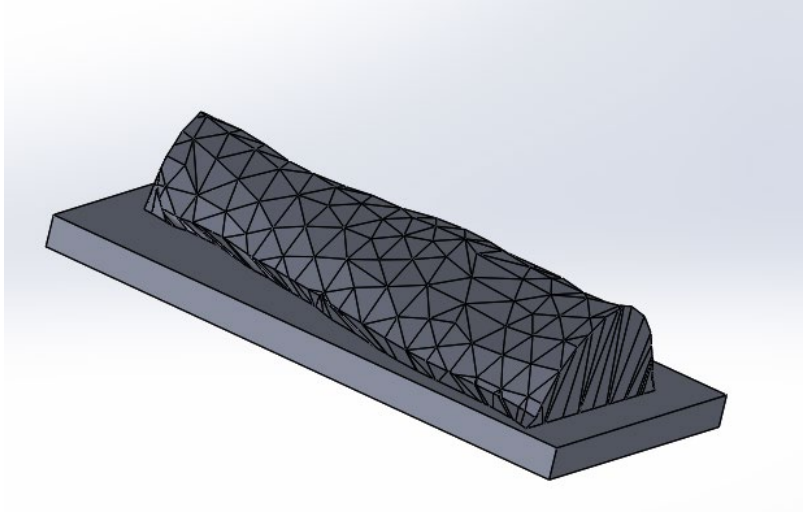


Figure 16. Extruded box combined with the imported scan

Next, I used the “Fillet” command and smoothed out the four edges of the top of the mold, using a radius of seven millimeters. This smoothed out the outer corners of the mold, as shown in Figure 17.

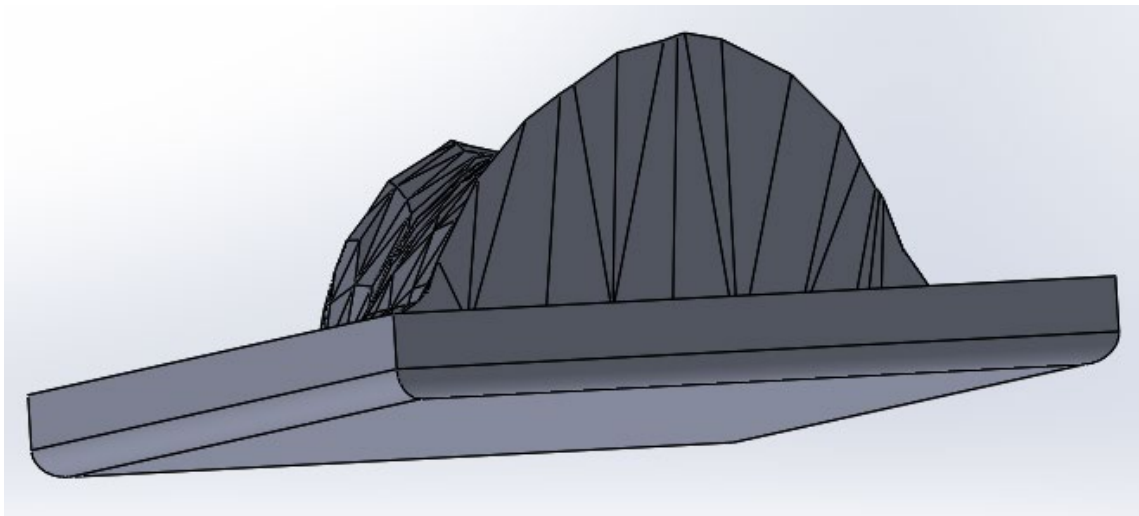


Figure 17. Top mold with filleted surface

Pockets of trapped air present a problem for our molds. If the air were trapped inside the cavity, it could prevent the casting material from filling the entire cavity. Even small air bubbles degrade the shape of our panels. To prevent air pockets from forming, I needed to put holes in the top piece. These holes would allow the air to escape when the two pieces are pushed together.

To create these holes, I made another reference plane along the face of the handle. I sketched circles along this surface at desired spots for the holes. Each circle had a five-millimeter diameter. Then I used the “Extruded Cut” command, opting for a blind cut extending out for 100 millimeters. Figure 18 depicts the side view of the “Extruded Cut” and Figure 19 depicts the finished version of the top mold.

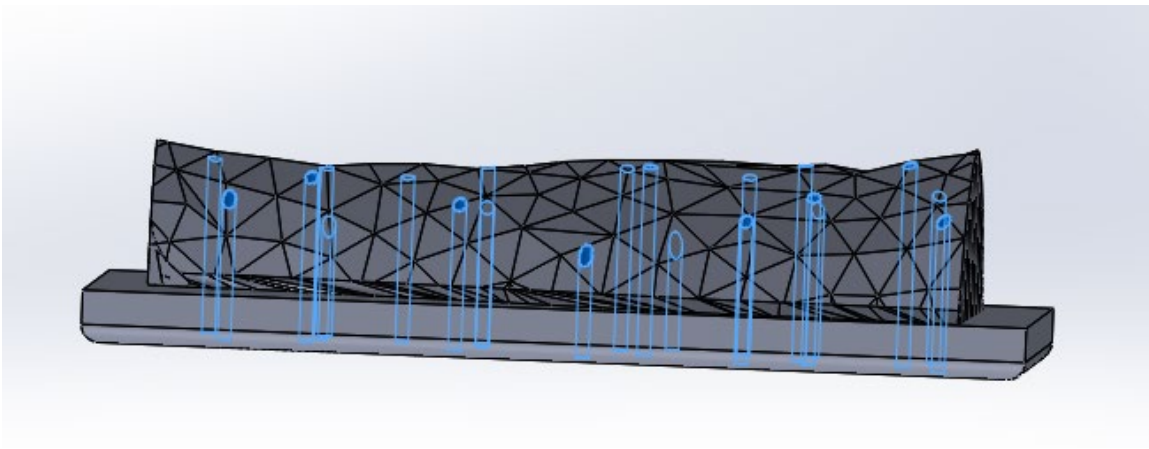


Figure 18. Extruded cuts through the top mold

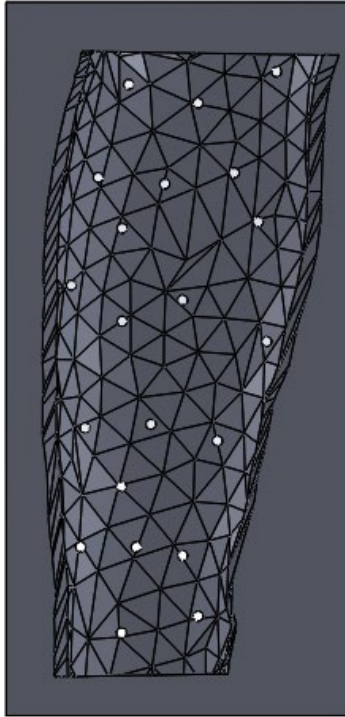


Figure 19. Final top piece with holes for air

The result from the cut were holes that extended through the entire top piece. Any trapped air and excess material would later escape through these holes during the casting process.

Once the top and bottom pieces for the left shin were finished, they could easily be copied over to make right sided pieces, as seen in Figure 20. I first created a reference plane along one of the side faces, offsetting it by 10 millimeters, and used the “Mirror” command. For this command to work properly, it was important to select the original piece in the “Bodies to Mirror” category, not as a face, feature, or plane.

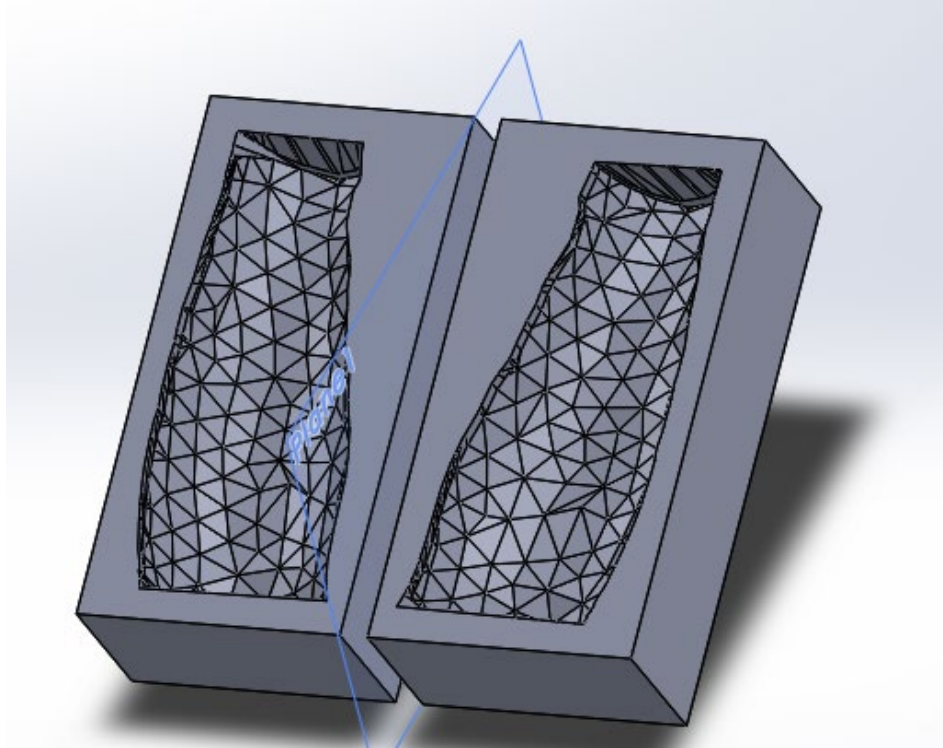


Figure 20. Bottom left shin mold being mirrored about a reference plane

This process was repeated for the left and right shoulders and forearms. The right thigh mold created by LT Demers and LT Martin also needed to be mirrored in order to create a left thigh mold. Once all the files were saved as STL files, they were ready to be 3D printed.

III. BUILDING THE WETSUITS

A. 3D PRINTING

3D printing was chosen as the ideal manufacturing process for these molds. The complex shape of the molds was much easier to create using a 3D modeling software such as SolidWorks than it would have been physically, and once we had a 3D model, printing it was straightforward. Other benefits to this method were the speed, cost, flexibility of material, and accuracy of the of the printing.

For the purposes of this research, we used the Fortus 400mc 3D Printer at NPS. A picture of this system is shown in Figure 21. This printer has a build envelope of 14x10x10 inches and is capable of printing within an accuracy of .127 millimeters [13].



Figure 21. Fortus 400mc 3D printer. Source [13].

3D printing also presents a long-term solution for producing large quantities of the composite wetsuit. The files for the molds can be easily resized for different users and instantaneously sent across the country to be printed.

In this case, our material requirements were not highly specific. We needed a material that was cheap, relatively strong to withstand the casting process, and could handle temperatures well above 80° C. The polycarbonate thermoplastic was selected as the ideal material to print our molds from because it can withstand temperatures ranging from -40°C to 140°C and has a higher flexural strength, tensile strength, and flexural modulus than other available thermoplastics like ABS [14]. This was important because our molds were cured in an oven at 80°C and opening the molds after curing required intense prying and pulling on the molds.

Due to the COVID restrictions, Mr. Daniel Sakoda operated the 3D printer and handled all the requested jobs for us. None of the molds took longer than 24 hours to print, leading to quick turnaround times of only a couple of days once the STL files were finalized.

B. CASTING PROCESS

The casting process was straightforward for myself and my lab partner, ENS Jared Young, thanks to the research done by Capt. Brown, LT Demers, and LT Martin.

Due to Capt. Brown's research on composite thermal properties, we knew that the 3M K1 glass microspheres demonstrate a better thermal resistivity than neoprene at depth. These glass microspheres could be embedded into Sylgard 184 polydimethylsiloxane (PDMS), an elastomer, in order to form a rubbery composite material. We also knew that the best bead volumetric percentage we could achieve was around 53%, as shown in Figure 22. Ideally, an even higher volumetric percentage would increase the thermal properties of the composite panels, but the highest achievable bead density was found to be 53%.

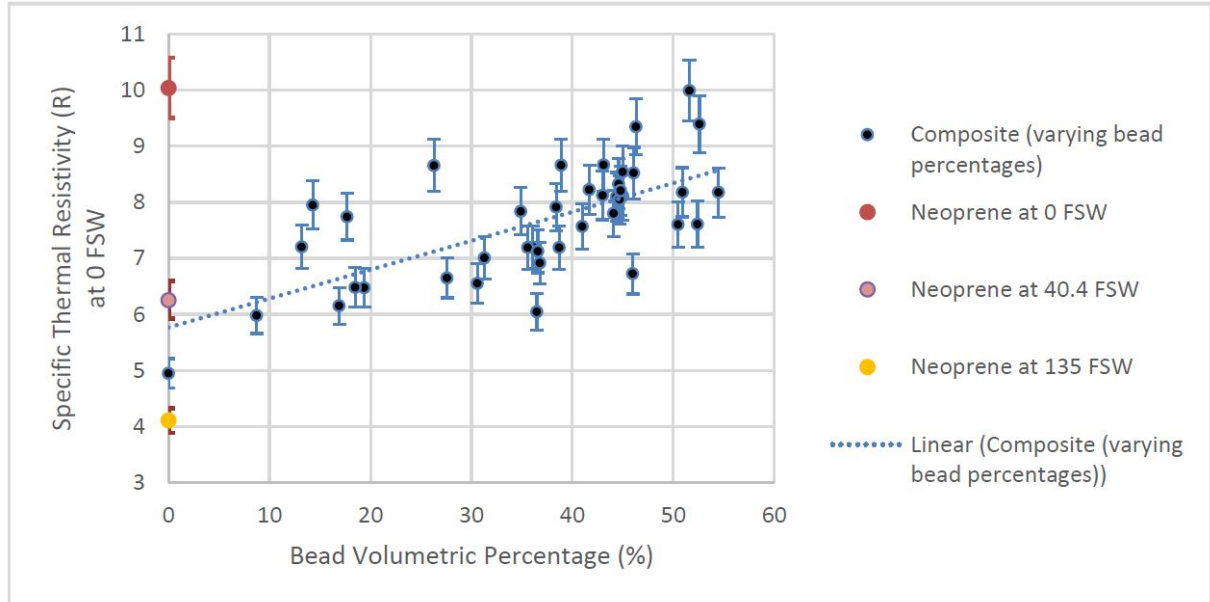


Figure 22. Thermal resistivity as a function of glass microsphere bead percentage. Source: [10].

We were able to follow the procedure outlined by LT Martin and LT Demers in their theses to create panels for ourselves. Boxes of Sylgard 184 PDMS were provided by Dr. Kartalov, each containing 0.453 kg of a silicone elastomer base and 0.0454 kg of a silicone elastomer curing agent, both from Ellsworth Adhesives. A large, 40-pound container of 3M K1 glass microspheres was also provided by Dr. Kartalov.

First, we added the Sylgard 184 elastomer base and curing agent into cups with a 10:1 respective ratio. In order to maintain a consistent ratio, we used a VWR E-series 1000-gram balance to measure each mixture. We started by zeroing the balance with the empty cup, then adding 100 grams of the elastomer base and 10 grams of the curing agent. We then added the 3M glass microspheres until the cup was approximately 53% glass microspheres by volume. This would nearly fill the cup each time. However, it was important to leave some space so that the mixing would be effective. Figure 23 shows my lab partner, ENS Young brushing the glass microspheres into the elastomer.



Figure 23. ENS Jared Young brushing glass microspheres into the elastomer

In order to embed the glass microspheres into the elastomer, we mixed the elastomer base, curing agent, and microspheres in an ARE-310 rotary mixer. The ARE-310 rotary mixer is made by the Japanese company THINKY Inc. and uses a 45-degree-rotation along with the normal centrifugal revolution to mix high and low viscosity materials. This combination of revolution and rotation with a 45-degree-tilt creates a three-dimensional flow of liquid that produces strong shearing forces [15]. This allows for a better dispersion of the glass microspheres, as seen in Figure 24.

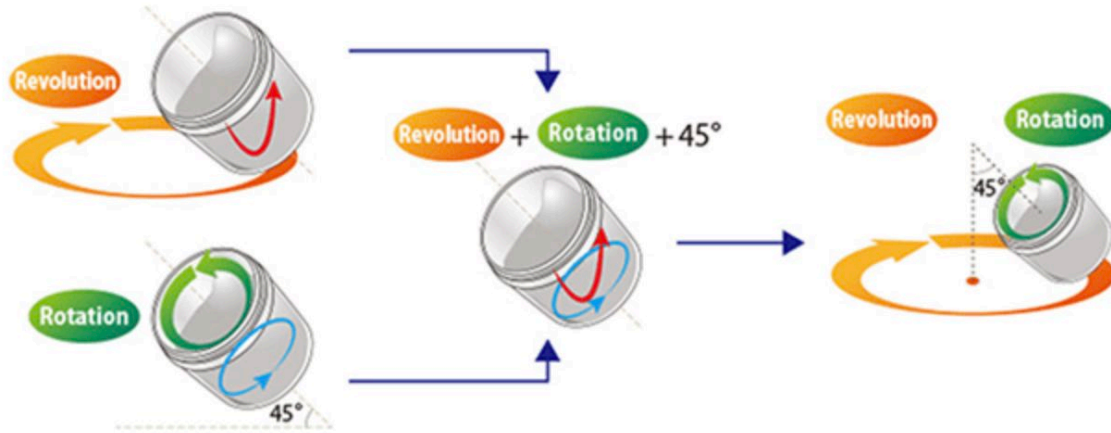


Figure 24. Depiction of how the ARE-310 rotary mixer combines rotation, revolution, and tilt to mix liquids. Source: [15].

For our composite panels to achieve the desired thermal insulation, it was important to have an even dispersion of microspheres within the liquid before it was cured. Another benefit to the intense shearing forces within the liquid was that it helped to destroy air bubbles that formed in the mixture, shown in Figure 25. When the air bubbles rise to the surface of the liquid, they are destroyed by the shearing force, which has a larger surface area due to the tilt of the cup [15]. These air bubbles would reduce the strength of our composite material and make it more susceptible to compression at depth, so it is important that they are minimized during the mixing process and degassed afterward.

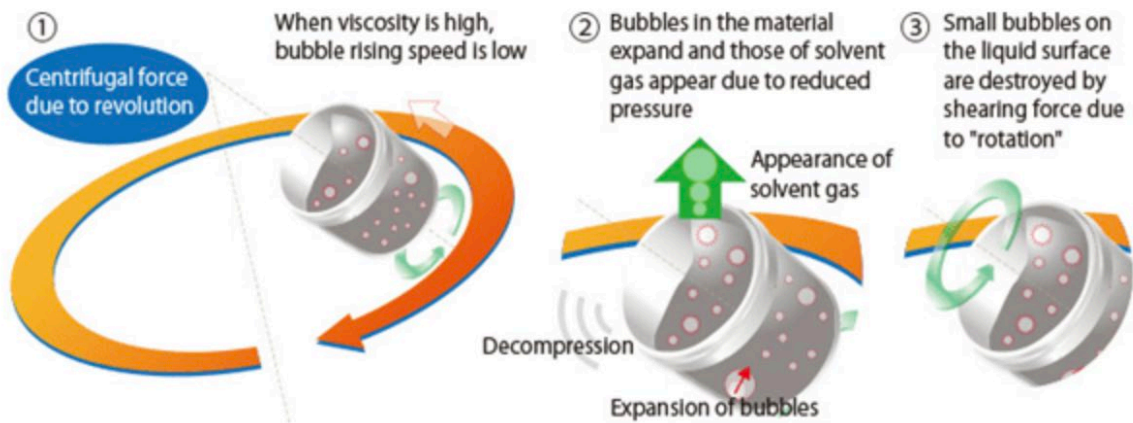


Figure 25. Depiction of the ARE-310 rotary mixer destroying air bubbles in the mixing process. Source: [15].

The rotary mixer was set to 1500 rpm and four minutes in order to mix the microspheres into the elastomer. The setup of the rotary mixer is depicted in Figure 26. We did not exceed speeds of 1500 rpm to avoid the risk of the microspheres breaking. After the four minutes of mixing, the cups were examined to ensure that the microspheres had mixed into the elastomer and that the resulting casting material had a relatively uniform texture.



Figure 26. Rotary mixer ready to mix the casting material for four minutes at 1500 rpm

After verifying that the glass microspheres were mixed into the elastomer, we needed to degas the mixture. In the mixing process, air bubbles would form inside the cups which, if poured into the molds, would expand during the heating process. This would leave small pockets and gaps within the panels, making them more susceptible to compression.

We used a vacuum chamber to degas the mixture. After mixing four or five cups worth of the liquid composite casting material, we opened each of the cups and placed them into the vacuum chamber. Once the vacuum pump was turned on, it would remove air from the chamber and the liquid composite would rise due to the drop in pressure. Just before the liquid composite would overflow from the cups, the pump was turned off and the liquid composite would condense back into the cup. Each time, the air inside the mixture would rise to the top and separate from the mixture. This process was repeated four or five times.

Now that the liquid composite was degassed, it was ready to be poured into the molds, as seen in Figure 27. Each mold required a different amount of liquid composite based on its volume, with the smallest requiring one and a half cups and the largest

requiring four. It was generally better to overpour the liquid composite because not pouring enough would result in an unusable panel.

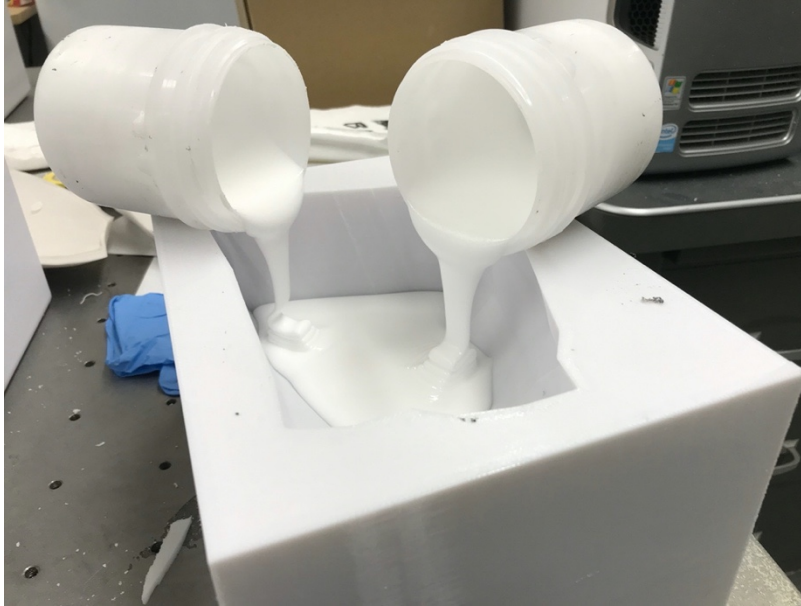


Figure 27. Liquid composite pouring into the mold

The liquid composite casting material then needed to be cured into the desired solid panel. We placed the top section of the mold over the bottom section and slowly compressed it until it sealed. If enough of the casting material was poured, the cavity between the top and bottom molds was completely filled and the liquid would start to rise up the holes in the top mold. We then placed the mold into the oven for curing, which takes two hours at 80° Celsius. Although this was generally enough time for it to cure, we would also allow it 24 hours at room temperature to fully solidify before trying to open the molds. The oven was large enough to fit multiple molds at a time, as shown in Figure 28.



Figure 28. Molds with liquid composite being placed in the oven

Once the liquid was cured into a solid panel, we had to open the molds to get the panel out. This was much more challenging than anticipated because the composite material would stick to the top and bottom parts of the mold, as shown in Figure 29. The best method to separate the molds was to work a flathead screwdriver between the top and bottom parts and use leverage to pry it open.



Figure 29. Left chest mold (left) and right shin panels (right) stuck to the top and bottom molds, respectively

Even after the molds were opened, the panels would often stick to one side of the mold. When this happened, it was important to slowly pull or pry the mold off, as it could easily rip if done too forcefully. Now that the panels were finally free, they needed to be trimmed down. First, all of the appendages that formed from the holes in the top mold needed to be cut off with a box cutter. Also, there were often edges that needed to be trimmed or smoothed down, as depicted in Figure 30.



Figure 30. The author shown trimming the left chest panel

This casting process was repeated in order to make two full composite wetsuits. In addition to the seven original molds from the initial version of the composite wetsuit, we created molds for a left thigh, right and left shin, right and left shoulder, and right and left forearm. The thigh pieces were used both on the front and back, and therefore we required two left thigh and two right thigh panels for each person. To complete our two wetsuits, we made eight thigh, two abdomen, four back, four chest, four shoulder, four forearm, and four shin panels. Figure 31 shows some of the completed panels.

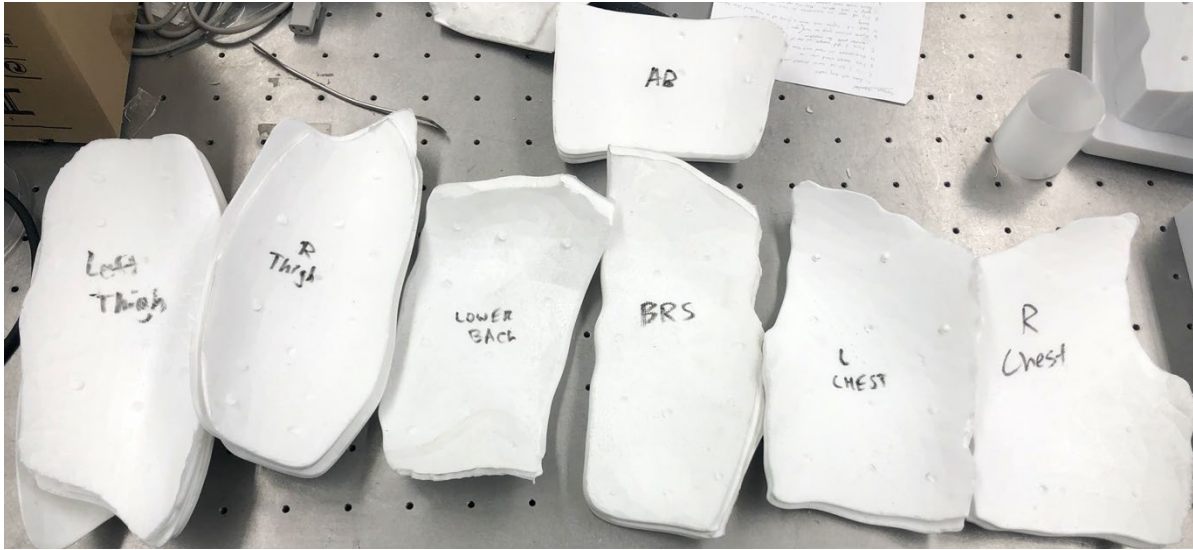


Figure 31. Initial batch of completed panels

C. SUIT FABRICATION PROCESS

Rather than testing our own adhesives, we decided to outsource the fabrication process to Otter Bay Wetsuits, a local wetsuit company that specializes in custom wetsuits. They used a blind stitch machine to sew the base of our wetsuit, as shown in Figure 32. This machine had a curved needle and a platform which automatically picked up the nylon material, allowing them to sew thin neoprene material on both the inside and outside.



Figure 32. Blind stitch sewing machine for wetsuits

Our baseline wetsuits were 4/3 mm neoprene, and since the pocket material added more material to this, the pockets could not be sewn on with this machine. Instead, Otter Bay Wetsuits used contact cement, also known as neoprene cement, to glue the pockets to the wetsuit.

Before that, ENS Jared Young and I went in to have the panels fitted onto our bodies, so that we could have them trimmed as needed and so that the outlines of the pockets could be marked by the people at Otter Bay Wetsuits. This process is depicted in Figure 33.



Figure 33. ENS Jared Young being fitted for his back left thigh (left) and left shin (right) panels

The white dots in Figure 33 show the outlines of the panel and allowed the people at Otter Bay Wetsuits to have a reference point for where the panels fit onto the wetsuit. It also gave them a size and shape estimate when cutting the material for the pockets.

Once the pockets were cut and glued onto the wetsuits with the panels inside, the suits were finished and ready to be tested, as shown in Figure 34.



Figure 34. Finished composite wetsuit

IV. TESTING

A. FINAL WETSUIT ADJUSTMENTS

After using my composite wetsuit to complete the PADI open water dive course, I noticed that the neoprene pockets had holes in them, allowing water to pass in and out of the pockets. This nullified the thermal effects of the composite material within the pockets. I also noticed that the shin and forearm panels were allowing water into the wetsuit. The shin and forearm panels extended down to the openings of the wetsuit on the ankles and wrists, and since the composite material is stiffer than the neoprene, it led to a gap between the body and the neoprene. This had to be fixed because the gap allowed more water to pass in and out of the wetsuit, further compromising its ability to keep the user warm.

The solution was to trim the forearm and shin panels by roughly two inches so that there was enough neoprene to fit tightly around the body at the openings where the water could get in. While the wetsuit is designed to take in water, only a small amount of water is meant to get into a wetsuit so that the body can heat it up. Ideally, this layer of warm water stays trapped against your body, preventing heat loss. When too much water gets into a wetsuit, it causes continual heat loss to the user because the cold water cycles in and out of the wetsuit. In order to make the proper repairs, more neoprene cement was needed to fill the holes that were found and reseal the panels that were trimmed. These repairs and modifications unfortunately cost the project roughly two months in delays.

B. EQUIPMENT AND DATA COLLECTION

I used four OM-CP-PRTEMP1000 rugged pressure and temperature data loggers to collect data from dive experiments. These temperature and pressure loggers use a thermistor to record temperatures with an accuracy within 0.9°F and can withstand temperatures between -40 to 176°F [16]. The pressure sensor used a strain gauge to measure the pressure within a 2% accuracy [16]. The exterior of the temperature and pressure loggers was made of stainless steel and could withstand depths of up to 230 feet in seawater [11]. The OM-CP-PRTEMP1000 data loggers are approximately six inches long and plug into the computer via USB, as shown in Figure 35.



Figure 35. OM-CP-PRTEMP1000 pressure and temperature data loggers

As seen above, the stainless-steel casing for the data loggers screws open in order to plug in to the computer. In order to maintain a watertight seal when closed, the threading contains an O-ring at its base.

Before each dive, I plugged the data loggers into the computer and used the OM-CP data logger software to start each one manually. Each data logger was serialized, but I gave each one a name in order to easily identify the data from different data loggers. I used a recording interval of thirty seconds on each of the dives. When the dive was completed, I plugged each data logger in to stop the recording and download the temperature and pressure data. This would generate a graph of the raw data, as seen in Figure 36. I would then change the temperature recordings from Celsius to Fahrenheit and export the data to excel, in order to trim out the time that was not spent in the water and create my own graphs.

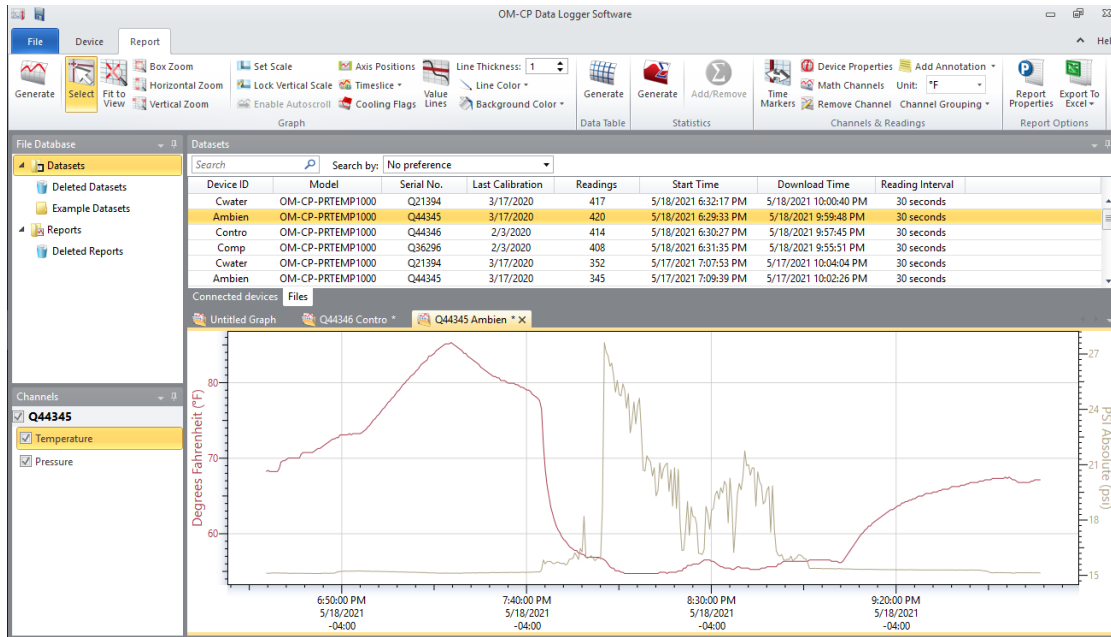


Figure 36. Omega data logger software

After taking out the data before and after the dives, I needed to convert the pressure readings in psi to depth in feet. I used Equation 1 to approximate the depth in feet, using the hydrostatic equation and solving for height h .

$$h = \frac{(P - P_{atm}) \times 6894.76 \frac{Pa}{psi} \times 3.28084 \frac{feet}{m}}{\rho \times g} \quad 1$$

where ρ represented the density of seawater, 1023.6 kg/m³, g represented the gravitational constant, 9.80665 m/s², and P_{atm} represented the standard atmospheric pressure at sea level, 14.6959 psi. The constants 6894.76 and 3.28084 were factors used to convert psi to pascals and meters to feet, respectively.

I generally stayed close to my dive partners in each of my experiments to have similar depth and ambient temperature readings. However, this was not always possible. In order to make sure that the data for each experiment was comparable, the temperature was recorded both inside and outside of the wetsuit for both the composite and control wetsuits. Additionally, this would ensure a proper comparison between experiments, as each experiment would have varying ambient temperatures. To be able to compare

different experimental data, I used the same parameter, delta temperature, as LT Martin did in his experimentation [11]. Delta temperature was defined as the temperature outside of the wetsuit subtracted from the temperature inside the wetsuit, as shown in Equation 2. This would be used to measure how well each wetsuit was keeping its user warm.

$$\Delta T = T_{inside} - T_{outside} \quad 2$$

For each of the experiments, the delta temperature in degrees Fahrenheit and depth in feet were plotted as a function of time.

C. DIVING EXPERIMENTS

My diving experiments compared my composite wetsuit to various 7mm wetsuits. For the purposes of the experiments, 7mm commercial wetsuits were used as the control data because it is a thickness commonly used by Navy divers. For each dive, one data logger was put in the chest area of myself and my dive partner. This data logger would measure the temperature inside of our wetsuit to gage how well our wetsuits were insulating our body temperature. A second temperature logger was attached to our BCDs to measure the ambient temperature of the seawater and the pressure, which was later converted to determine our depth.

For future research purposes, the age, height, and weight of each diver was recorded to see if that made a considerable difference in thermal insulation. At the time of the experiments, I was 23 years old, five feet, nine inches tall, and weighed 160 pounds.

In addition to basic biometrics, it was important to note the types of wetsuits used by my dive partners, since they varied from dive to dive. One of my dive partners used an open-cell wetsuit, which I had not heard about due to its rarity. Open-cell wetsuits are sometimes used for freediving, and generally provide better thermal insulation than closed-cell neoprene wetsuits. This is because there is no nylon layer between the neoprene and the skin in an open-cell wetsuit, and it is almost impossible for water to get inside due to the neoprene sticking to the skin [17]. The reason these open-cell wetsuits are far less

common than closed-cell is that they can tear much more easily and require lubricant to get into.

1. Experiment 1 20APRIL2021

After several weeks of waiting for the wetsuit to be repaired, I was ready to start testing. The first dive experiment took place at Breakwater Cove in Monterey, CA. My dive partner collected the control data using a standard 7mm, closed-cell neoprene wetsuit. His height was six feet, two inches and his weight was 190 pounds. He was 23 years old at the time of the dive experiment.

As I entered the water, I noticed an abnormal amount of cold seawater rush into my wetsuit from my ankles up to my calves and thighs. After about a ten-minute surface swim, we descended. Unfortunately, the visibility was extremely poor that day, and we lost each other while trying to descend. After about a minute of trying to find each other, we surfaced, as per the standard safety procedure.

After meeting up on the surface, we swam for about twenty minutes to an area we hoped would have better visibility. We descended again, this time staying on the bottom for approximately twenty minutes, with an average depth of around forty feet. During the dive, I felt no difference in temperature between the surface and forty feet.

As I walked out of the water, I noticed that seawater was flowing out of the pockets. This meant that the pockets were still leaking, and that seawater had been in them the entire time. With the seawater being able to circulate freely on the inside of the composite panels, they could not make any impact on the thermal insulation of the wetsuit. This meant that I had to get my wetsuit repaired and adjusted again.

2. Experiment 2 17MAY2021

Once my wetsuit was repaired, I was ready to continue my dive experiments. The second dive took place at Monastery Beach in Monterey, CA. My dive partner for this experiment was ENS Jack McMahon, who used a 7mm, open-cell neoprene wetsuit. His height was five feet, nine inches and his weight was 185 pounds. He was 23 years old at the time. The dive lasted approximately one hour with the first fifteen minutes consisting

of a surface swim. After descending, much of our time was spent between thirty and fifty feet. Our maximum depth was eighty feet.

One of the takeaways from this dive was the difference in mobility between myself and my dive partner. Due to better visibility, I noticed that I had a much better range of motion, particularly in the shoulders, than my dive partner. Swimming and moving around was as easy as it is in the 3mm wetsuit that I own for surfing.

Unfortunately, I still noticed a considerable amount of water coming into the wetsuit. This time, the pockets were not noticeably leaking. I determined that the water could have been coming in from the openings on the wrists and ankles, as I was wearing my gloves and boots under the wetsuit. My gloves and boots were by no means watertight and were likely letting water in under the openings on the wetsuit, which would then circulate inside the body. For the next dive, I would try wearing the gloves and boots over the wetsuit. This would allow water to freely flow into my hands and feet but would hopefully reduce the amount of water coming into my body from the wrists and ankles.

3. Experiment 3 18MAY2021

The next day, I dove again with a different dive partner, ENS John Lee. He used a 7mm, closed-cell neoprene wetsuit. His height was five feet, nine inches and his weight was 142 pounds. He was 23 years old at the time of the dive experiments. Unfortunately, the area we dove in was not as deep as we were hoping, so the dive was mostly spent at depths between fifteen to twenty feet. The dive lasted approximately one hour.

As mentioned, for this experiment I dove with my gloves and boots on the outside of my wetsuit in an effort to have a better seal around my wrists and ankles. This felt like it improved the water flow from the wrist openings, but the seal around the ankles did not feel tight.

Throughout the dive, even at the surface swim in the very beginning, I felt cold surges of water in the back and legs. When I took off the wetsuit after the dive, I noticed that a seam had burst from the inside of the wetsuit, creating holes along the stitch pattern and allowing water to come directly inside the wetsuit through the lower back. This would explain the cold

surges I felt from the beginning of the dive, however, I was not entirely sure if the hole was there before the dive started or if it occurred during the dive. The holes were large enough that my fingers could be seen through the material, as shown in Figure 37.



Figure 37. Hole in the back of the composite wetsuit

Unfortunately, this hole meant that I needed to get my wetsuit repaired again, as the water flowing in from the back completely compromised the wetsuit.

4. Experiment 4 25MAY2021

Thankfully, the repairs were quick, and I was able to get back to diving in the following week. From the previous experiments, I knew that I had to do everything I could to minimize the water leaking into my wetsuit. Only then would I start to notice the thermal effects of the composite panels.

My solution was to tighten the openings around the wrists and ankles using neoprene Velcro that I got from Otter Bay Wetsuits. Ideally, this would further limit the water flowing into the wetsuit and allow me to properly measure the thermal effects of the composite material.

For this experiment, I put the gloves over the wetsuit, and tightened the neoprene Velcro cuffs over the glove, as shown in Figure 38. Although the neoprene underneath cannot be seen, the Velcro is tightened down over neoprene at the top of the wrist in order to create a better seal.



Figure 38. Wrist opening with gloves and Velcro cuff

For the ankles, I put the boots under the wetsuit and the Velcro cuffs on top, as seen in Figure 39. Due to the zipper on the boots and how far they go up the ankle, this configuration made the most sense. With the Velcro cuff on top, it would hopefully be able to tighten down all the layers under it and improve the seal.



Figure 39. Ankle opening before (left) and after (right) Velcro cuffs

This dive took place at Breakwater cove, with ENS John Lee as my dive partner. He used the same closed-cell, 7mm neoprene wetsuit. The dive lasted approximately one hour with most of the time spent at around forty feet. For the most part, I did not feel much water coming into my wetsuit during the surface swim at the beginning, mostly just small amounts through the back. When we descended, however, I felt water rushing into the suit from the opening on the neck. During the dive, I felt multiple cold surges in my back and on the back of my thighs. Strangely, I did not notice any cold water coming into the suit from the wrists or ankles. Instead, I consistently found that my hands and feet felt far colder than my shins and forearms. This led me to believe that the water was not leaking in from the wrist and ankle openings, but somewhere else in the wetsuit.

At the end of the dive, I noticed that my dive boots and gloves were filled with water, but that the Velcro seals were successfully stopping the water at the wrists and ankles. I concluded that the neck opening was too loose, allowing water into the wetsuit. I also suspect that water was leaking in through the backside of the wetsuit, though much

more slowly. Due to time constraints, this was my last dive experiment, so I was not able to make more adjustments in order to stop the leaking. If I had more time, I would have looked into constructing a new composite wetsuit, given the continual problems with current one.

V. RESULTS AND DISCUSSION

A. DIVING DATA

1. Experiment 1 Data

The data from the first experiment showed that the wetsuit was leaking and therefore did not properly insulate the user. As seen in Figure 40, the delta temperature of the composite wetsuit dropped off dramatically within the first ten minutes of the dive, during the initial surface swim. Because my temperature declined before we even descended, it was concluded that water leaked in from the beginning and that the constant circulation of cold water is what kept my temperature low for the entirety of the dive. The delta temperature of the composite wetsuit levelled off at around twenty minutes into the dive, at roughly 13°F.

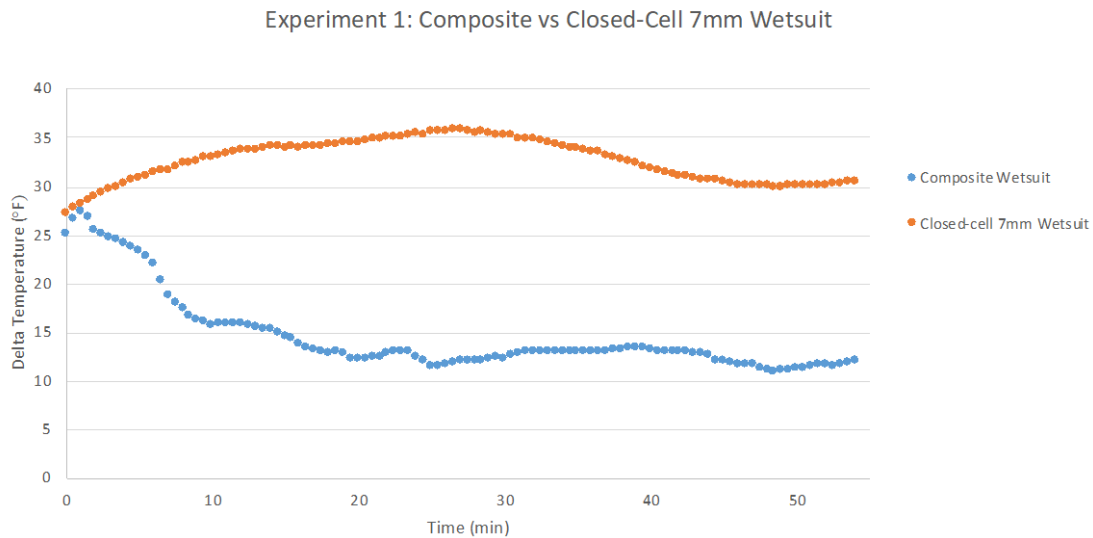


Figure 40. Experiment one delta temperature

The temperature data from the first experiment confirmed what I had already noticed from the dive, that water was getting into the pockets and even the wetsuit. It was

time to get the holes in the pockets fixed, as the effects of the composite panels would not be noticeable with these holes in the wetsuit.

Meanwhile, the closed-cell 7mm wetsuit greatly outperformed any of the control wetsuits used in the experimentation from LT Martin. In experiment one, the closed-cell 7mm wetsuit reached a maximum delta temperature of 35°F and levelled off at 30°F. In comparison, the 7mm control wetsuit used in LT Martin’s experiment five recorded a delta temperature starting at 15°F that slowly declined to 10°F [11]. This inconsistent data was concerning, so I decided to switch the temperature loggers used for the control and composite wetsuits for the next experiment.

Figure 41 shows the depths recorded in our first dive experiment. Due to the poor visibility, we were not able to find each other in our initial descent and had to resurface and swim to another area with slightly better visibility.

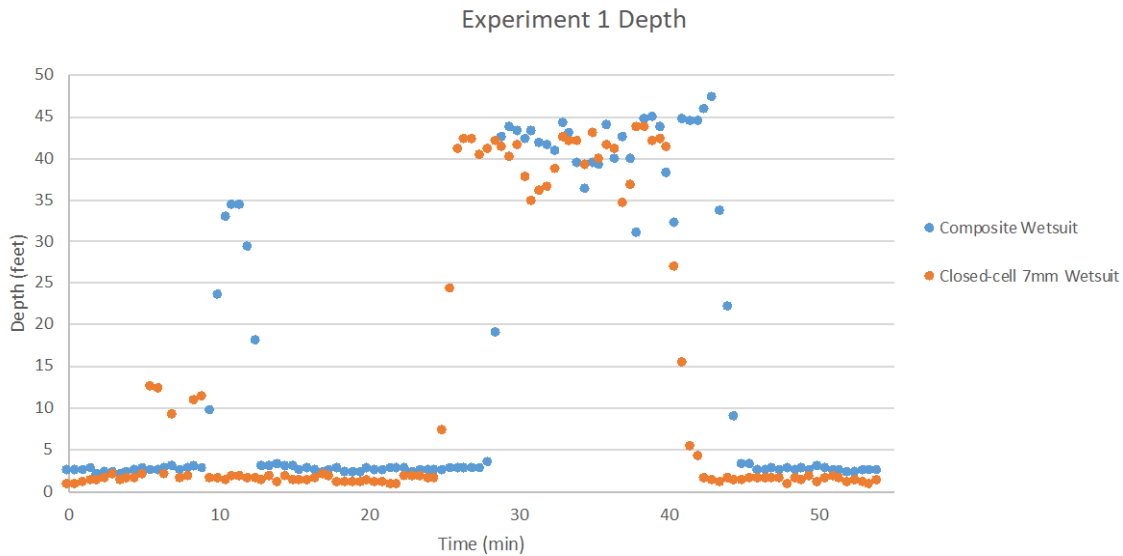


Figure 41. Experiment one depth

An important lesson from this experiment and the subsequent repairs was that the smaller gluing margins made it far more difficult for Otter Bay Wetsuits to fully seal the pockets. These gluing margins were the distance between where the panel and the pocket

ended on each side. For the Mk1 wetsuit made by LT Martin, the gluing margins were an inch, whereas for this wetsuit they were half of an inch. This means that there was less extra neoprene material that was glued down to make the pockets, making it harder to have a reliable seal.

2. Experiment 2 Data

After the first experiment, I came to the conclusion that the holes in the pockets were causing the poor thermal performance of the composite wetsuit. While it certainly had an impact, experiment two showed that the wetsuit was also taking in water from another area. Even after the pockets were thoroughly sealed, the data for the composite wetsuit was roughly the same. As seen in Figure 42, the composite wetsuit levels off at 13°F. The open-cell 7mm wetsuit had good thermal properties, peaking at 37°F and levelling off at 29°F.

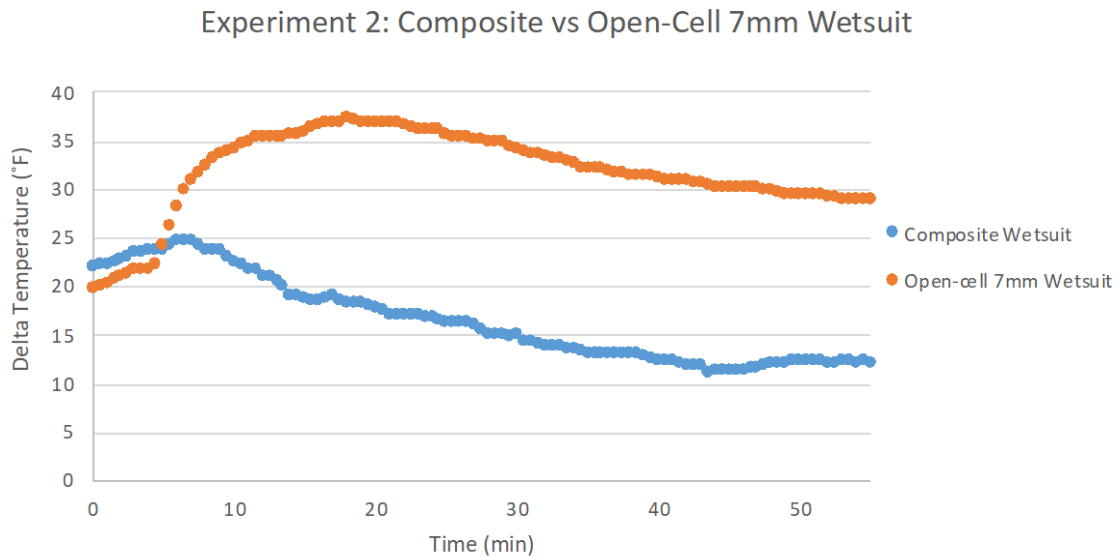


Figure 42. Experiment two delta temperature

Since the visibility was far better on this dive, we were able to stay much closer to each other and therefore had very similar depth data, as seen in Figure 43. An important note for this experiment was that it was considerably deeper than the previous one. After a

surface swim, we spent around thirty minutes at a depth of thirty or more feet, with three descents below fifty feet.

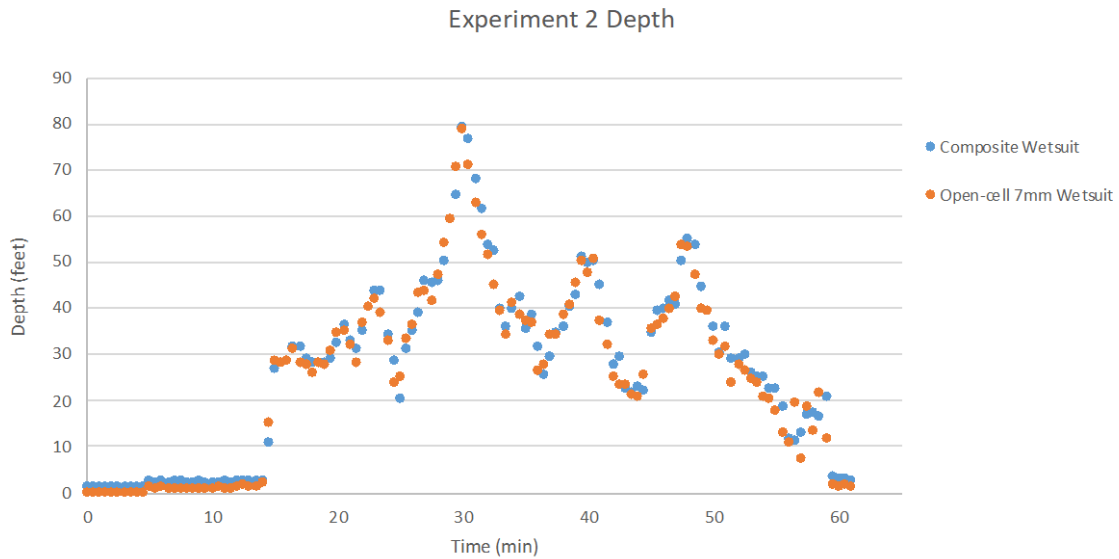


Figure 43. Experiment two depth

One difference from this experiment was that the decline in delta temperature was far more gradual in the composite wetsuit. Instead of dipping heavily at the very start, it appears that the water was getting into the wetsuit, but not instantaneously. This was still bad and caused poor thermal data for the wetsuit, but it means that the repairs did help. This gave me hope that if I could find the leak, we could get accurate data for the wetsuit. I concluded that the openings in the wrists and ankles were allowing the water in and decided that if I changed the configuration of my boots and gloves, I might be able to reduce the water coming in through the openings. I also would rotate the temperature loggers between this experiment and the next just to make sure it was not due to a defective data logger.

3. Experiment 3 Data

This dive was similar to the first one, in the sense that I experienced a sharp decline in delta temperature right at the start of the dive, before even descending. As seen from Figure 44, I was down to a delta temperature of 14°F within six minutes of entering the water, and levelled off at around 12°F. This supports the hypothesis that the hole in my lower back was there from the start of the dive, as the water circulated immediately through my wetsuit and lowered my temperature at the very start.

This closed-cell 7mm wetsuit did not perform as well as the other two control wetsuits, with the average temperature recorded at 22°F. This is odd, especially since this dive was not as deep as the others, as seen in Figure 45. This could be due to two main differences in ENS Lee's wetsuit. His wetsuit was a back-zip, and he had a tuck-in hood that went underneath the opening on the neck. My wetsuit was the same in these two aspects, but the control wetsuits for experiments one and two were both chest-zip wetsuits with built-in hoods.

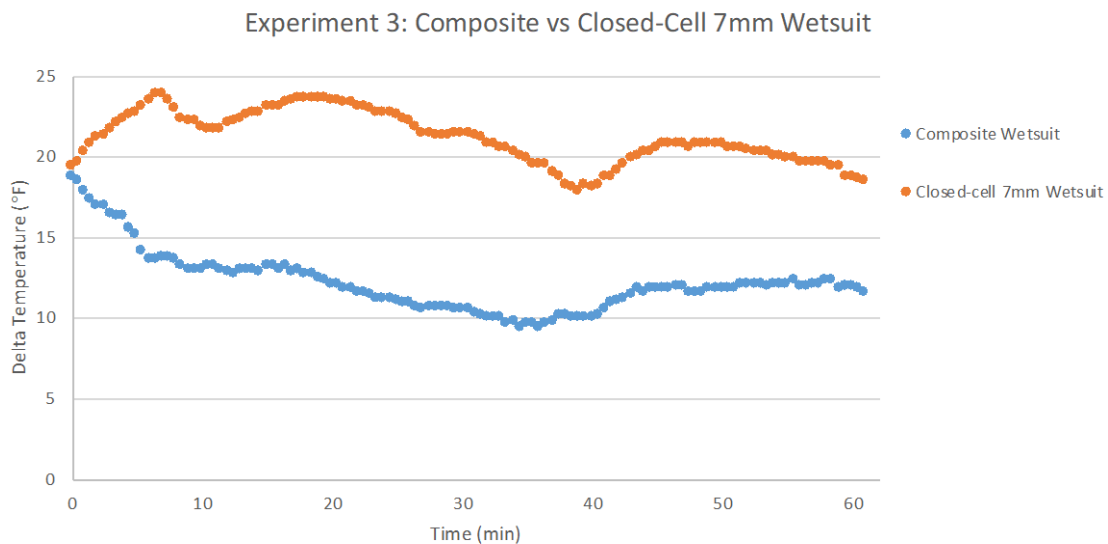


Figure 44. Experiment three delta temperature

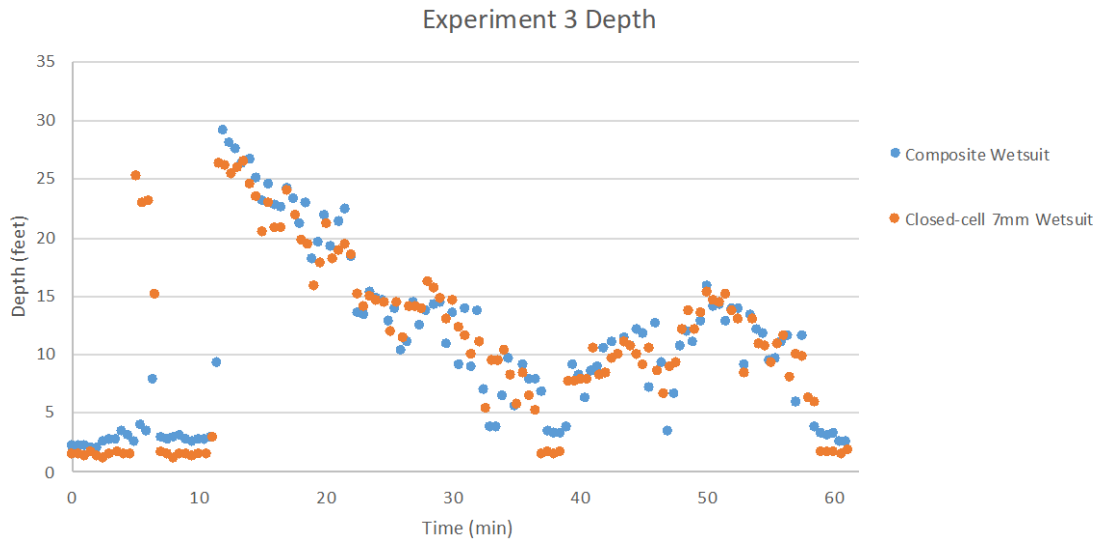


Figure 45. Experiment three depth

4. Experiment 4 Data

After three experiments with poor thermal data, I was hoping that the Velcro cuffs would solve the leaking issues with the wetsuit. This was not the case, as shown in Figure 46. While the Velcro cuffs appeared to have worked in limiting waterflow into the wrists and ankles during the dive, it seems that the wetsuit was still leaking from somewhere else. While there were large fluctuations in the delta temperature, the composite wetsuit averaged 12°F after the first twenty minutes of the dive.

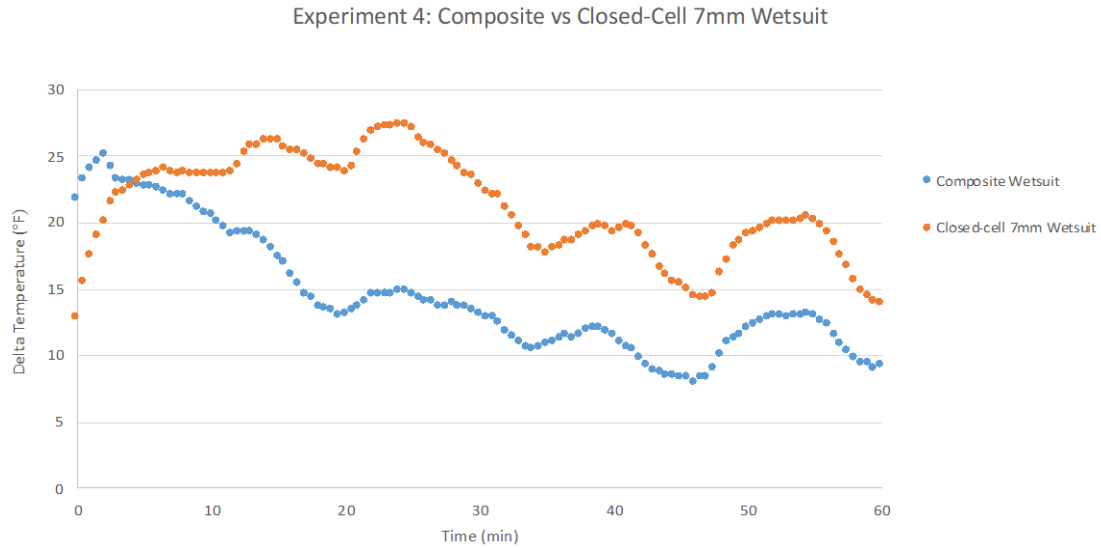


Figure 46. Experiment four delta temperature

Unlike in previous experiments, I did not experience sudden drop in delta temperature at the very start of experiment four. The drop came at around twelve minutes, as I was descending. This matches my dive notes and supports the hypothesis that the opening on my neck was allowing water into the wetsuit. This also suggest that the Velcro cuffs may have helped for the first ten minutes of the dive, before water got into the wetsuit from the neck.

The temperature data from experiment four was far less consistent for both wetsuits than in previous tests. This was due to fluctuations in the temperature of the ambient seawater with relatively consistent temperatures within the wetsuits. Figure 47 shows the depth data from experiment four.

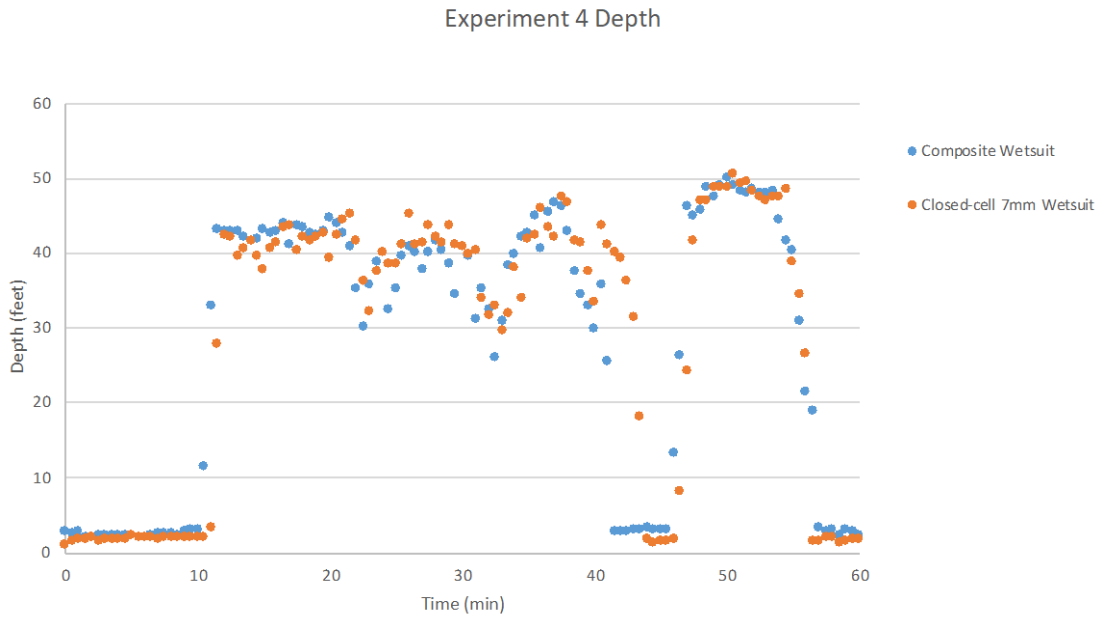


Figure 47. Experiment four depth

Unfortunately, I was not able to get the desired thermal data for my composite wetsuit. Despite attempts to limit the water that was flowing into the wetsuit, I was not able to fix the leak. The data did not support our hypothesis that the composite wetsuit would improve the thermal insulation of the user, but that does not mean the experimentation was in vain. There are many takeaways from this process and experimentation that can be useful to future students on the project.

B. KEY TAKEAWAYS

1. Limit Waterflow

The most obvious takeaway was that the wetsuit will not work as designed if water is able to enter the suit freely. No thermal improvement will be noticed from composite plates if the seawater is constantly getting inside the wetsuit. Wetsuits are designed to trap a small amount of water inside that the body heats up. The problem is that when the seals are not tight enough, seawater is constantly flowing, and the body loses heat to the cold seawater. Since limiting the water coming into the wetsuit is the most important aspect to

its thermal performance, I recommend that the next version of the composite wetsuit includes features specifically designed to reduce water flow.

2. Gluing Margins

Another important takeaway was that using extra neoprene material for the pockets helps to create a more reliable seal. The extra material should extend at least an inch in all directions beyond the composite panels, to allow space for gluing. This was an important lesson to learn because it took far longer to repair the wetsuit over multiple occasions than it would have to use larger gluing margins from the start. If there is not enough space between panels, it is preferable to trim the panels than to risk having an improper seal that could compromise the entire wetsuit.

3. Improved Mobility

The addition of extra panels in the forearms, shins, and shoulders without a loss of mobility was an important outcome of the project. These panels were especially difficult to incorporate because of their proximity to major joints in the body, such as the elbows, knees, and shoulders. However, the Mk2 composite wetsuit demonstrated that it was possible to maintain the mobility of a 3mm wetsuit, even with panels in these areas of the body.

Mobility is a key factor to the final composite wetsuit design because of the mission requirements of Navy divers in various communities. After all, mobility is the key reason that the Navy is looking into improved wetsuit designs, instead of using alternatives like dry suits that offer better thermal protection.

C. FUTURE TESTING

1. Smooth Skin or Glide Skin Coating

One potential solution to limiting the water that comes into the wetsuit is a smooth skin or glide skin coating. This was recommended by Otter Bay Wetsuits to help create a better neoprene seal around the wrists and ankles. To do this, we would take a layer of the skin material and put it on the inside of the wetsuit. This material would be glued around

the openings on the wrists and ankles and stick to the skin better than the nylon that is usually found on the inside of wetsuits. This is because the nylon material is porous, whereas the smooth skin or glide skin is not. This would be a feasible addition to the next version of the composite wetsuit because Otter Bay Wetsuits has this material.

2. Velcro Cuffs or Straps

Another solution that could be tested is continuing the use of Velcro cuffs or straps to tighten down the openings along the wrists and ankles. This would hopefully allow less water to circulate in and out of the wetsuit, allowing the body to stay warmer. In my last experiment I attempted to use these, but due to leaking in other parts of the wetsuit its effects were not measurable. Follow-on experimentation could yield an improvement in the thermal performance of the wetsuit and allow us to experiment with the composite panels more easily.

The neoprene Velcro material is readily available for the project, thanks to Otter Bay Wetsuits. The Velcro could be sewn onto the wetsuit, making it easier to tighten down under gloves or over boots. This could also be used to tighten the neck opening if it was placed on the neoprene above the back-zip.

3. Open-Cell Neoprene

Open-cell neoprene is known to have better thermal properties than closed-cell neoprene but has its own set of challenges. The most significant of these are the strength of the material and the ability to get into the wetsuit. While these are problematic, if they can be overcome, a wetsuit with open-cell neoprene and composite panels could provide even better thermal protection for the user. Due to the stiffness of the panels, the composite wetsuit is already difficult to get into, so this solution is unlikely. However, it is worth looking into, especially if the panels were made to be more flexible in future designs.

4. Different Hoods, Gloves, Boots

One variable that could affect future testing is the type of accessories used to keep heat in. I noticed in particular that many of my dive partners had thicker hoods, as well as gloves and boots that appeared to have better insulation and water resistance. While this is

not likely to cause the extreme disparities in the data, it is likely to have an impact. It is known that much of the heat loss in diving occurs through the head, so it may help to try tests with different accessories or standardize them between the composite and control wetsuits.

It was also noted that the back-zip versus the chest-zip could have made a difference in thermal data. The control wetsuits from experiments one and two were both chest-zips and outperformed the back-zip control wetsuit from experiments three and four. Unfortunately, due to the stiffness of the panels, the composite wetsuit has to be a back-zip for the user to be able to get into it. This distinction is important, however, because our final composite wetsuit needs to be able to thermally insulate divers better than all types of commercially available wetsuits.

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VI. CONCLUSION

The Mk2 wetsuit has helped prototype a composite design that will be the future for cold-water diving operations. This composite wetsuit will be able to protect future Navy divers from cold water exposure and hypothermia, allowing them to carry out their missions with a higher level of safety and efficiency.

From previous research, we know that the composite material used for the panels does not compress as much as neoprene and provides much better thermal insulation at depth. Although the thermal data of the Mk2 wetsuit did not show improved thermal insulation, this project helped to outline the procedures used and challenges faced when integrating these composite panels to the wetsuit.

One success of the Mk2 wetsuit was the mobility achieved despite the addition of more composite panels. The three-millimeter thickness around the joints, specifically the shoulders, elbows, and knees, make a significant difference in the diver's ability to move freely. This improvement will be even more distinct for Navy divers who have to weld underwater, recover sunken equipment, or defuse mines.

Future research is still required to continue to improve the balance between maximizing panel coverage and ensuring a proper seal within the wetsuit. Further iterations of the wetsuit will likely employ a design feature focused on reducing the water coming into the wetsuit. This will greatly improve the thermal performance of the composite wetsuit, allowing us to see more dramatic improvements at depth due to neoprene compression.

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