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**ENHANCED THERMAL INSULATION IN WATER
THROUGH THE USE OF GLASS AND CERAMIC
MICROSPHERES**

by

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December 2023

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OF GLASS AND CERAMIC MICROSPHERES**

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Submitted in partial fulfillment of the
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ABSTRACT

Maintaining body temperature has always been a concern for divers working in cold water. Failing to preserve warmth is not only a matter of comfort but can also lead to serious injuries and even death, primarily through an increased risk of decompression sickness, hypothermia, and other life-threatening conditions. According to the U.S. Navy dive manual, “Cellular neoprene wetsuits lose a significant portion of their insulating properties as depth increases and the material compresses.” Other NPS students have successfully applied the use of glass microsphere beads and ceramic microsphere beads in separate composite wetsuit designs that enhance warmth for divers at various depths. Previous researchers at NPS have discovered that the most effective method for applying the composite glass bead material to the body is through a 3mm wetsuit with 2mm neoprene pockets. However, the previous students did not apply the glass bead composite material to the head, nor did they use ceramic microsphere composite material in combination with glass microsphere composite material to insulate the diver and improve the ergonomics of the suit. In this research, I was able to develop a suit that keeps the diver warmer at depth than a standard off-the-shelf 7mm wetsuit, while also distributing weight evenly throughout the body, allowing the diver to move more ergonomically underwater.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACFM	Actual Cubic Feet per Meter
ATM	Atmosphere
BCD	Buoyancy Control Device
BPM	Beats Per Minute
EGS	Emergency Gas Supply
FSW	Feet of Sea Water
KM-37	Kirby Morgan 37
NCTRU	Navy Clothing and Textile Research Unit
NDSTC	Naval Dive and Salvage Training Center
PSIG	Pounds per Square Inch Gauge
RMV	Respiratory Minute Volume
SCFM	Standard Cubic Feet per Meter
SCUBA	Self Contained Breathing Apparatus

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I. INTRODUCTION

As a trained Navy salvage diver, the importance of staying warm underwater has been emphasized since I started dive school in the summer of 2021. It has also been a part of my personal life, growing up in San Diego and spending my time surfing or spearfishing in the cold waters of the Pacific Ocean. I continue to pursue these hobbies in Monterey, where it is especially crucial to maintain warmth, as the water temperatures frequently drop below 50 degrees Fahrenheit. A human cannot survive for long in the cold Pacific waters without proper thermal protection.

Over the years, I have experimented with various styles of wetsuits, including surf wetsuits, dive wetsuits, and spring suits, all with different thicknesses. All the wetsuits I have owned have been made of neoprene material. Not only have all the wetsuits I have personally owned been neoprene, but every wetsuit that I have worn while on official diving duty has also been neoprene. Despite the vast resources of the Navy, neoprene has been the material of choice for Navy Divers. However, there are two notable downsides to neoprene dominating the market: the reduced maneuverability it offers to the diver in the water, and when wearing thick wetsuits, the compressibility of the material decreases the thermal insulation of the neoprene at depth.

Staying warm is of utmost importance in the Navy due to the extended periods of time required to work in cold environments, the unique nature of the tasks that need to be accomplished, and the urgency of the mission. The common mission for Navy Divers is Underwater Ships Husbandry. This occurs when a Navy ship needs something fixed below the waterline, and the ship does not have the time or resources available to make it to a dry dock. Frequently, the dry dock has a schedule booked out years in advance. It is often less time-consuming to send divers to fix the problem rather than putting the entire ship into a dry dock. Divers can remain at a depth of 32ft for a maximum of 304 minutes without incurring decompression time [1]. This depth is deeper than what most Navy Divers will work at while performing Underwater Ships Husbandry. The decompression time is not the limiting factor with this type of work, but rather the fatigue of the diver and the ability for the diver to stay warm. The diver would be able to switch out for another diver if

available, but at a cost of efficiency. It takes several minutes to raise the diver and swap with another diver, sometimes on the order of 30 minutes depending on whether there is enough gear for the next diver to be fully dressed out and the experience of the dive team. The next diver will also take time to find the exact place he needs to be on the ship. It can take time to orient yourself, especially if visibility is low, which is commonly the case in major U.S. ports. If a job needs to be done quickly, it is best done by the divers already in the water.

A. A BRIEF HISTORY OF DIVING

The roots of diving can be traced back to further than 5000 years ago with the majority of diving confined to shallower than 100ft [1]. The diving bell is an apparatus that takes air from the surface environment and pushes it down so the diver has a pocket of air to breathe from. The design by Edmund Halley consisted of a wooden inner wall with an outer wall coated in lead. This lead coating helped to hold the bell at depth as well as maintain a seal. An early depiction of this method is shown in Figure 1.

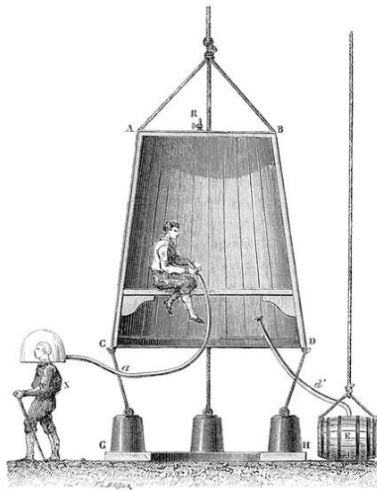


Figure 1. A diving bell designed by Edmund Halley (1656–1742). Source: [2]. Compressed air would be sent into the bell and stale air would be let out through a relief valve. Three weights are displayed at the bottom of the image.

This method limited the diver's mobility and what they could accomplish underwater. Soon, technological innovations allowed for more extensive exploration of the sea floor. Historically, the primary purposes of diving were the search for treasure, salvage efforts, and hunting for food. Diving today shares many similarities with its historical counterparts. Military strategists have long considered how to best employ this technology against adversaries. According to [1], "Alexander the Great sent divers down to remove obstacles in the harbor of the city of Tyre, in what is now Lebanon, which he had taken under siege in 332 B.C." Despite the human curiosity and the desire to explore the underwater realm, diving technology did not mature until the 1940s when Jacques Cousteau and Emile Gagnan invented the aqualung [3]. This remarkable invention, which made underwater diving possible, included a demand regulator that allowed the pressure in the diver's lungs to match the changing underwater environment's pressure [4]. The aqua lung company continues to thrive today, and their products are commonly found in most scuba shops across the country. Self-Contained Underwater Breathing Apparatus (SCUBA) is not the sole form of diving available to consumers today.

B. CURRENT TECHNOLOGY

There are various types of diving apparatus available, including SCUBA, surface-supplied, mixed gas, and rebreather systems. This thesis will focus on SCUBA and surface-supplied Navy Air diving operations due to the availability of resources and their status as the most frequently performed types of diving in the Navy.

1. Navy Air Diving Technologies

SCUBA is the most common underwater breathing apparatus available to the public, allowing recreational divers to stay beneath the surface for hours at a time. The major limitation of SCUBA is determined by decompression tables and the amount of air in a SCUBA tank. For example, the no-decompression limit for a SCUBA diver at a maximum depth of 60 feet is 63 minutes according to [1]. The shallower the dive, the longer the diver can stay underwater without needing to decompress. Having no decompression means that the diver can return directly to the surface without pausing for decompression. The Navy does not permit divers to perform any decompression using

SCUBA [1]. The civilian diving community occasionally employs this technique but is reserved for the highly experienced. The scuba tank used in the following experiments has a volume of 100 cubic feet, allowing a diver to remain at 60ft while moderately working for up to 24 minutes. The duration of the dive is calculated using

$$C = \frac{D + 33}{33} \times RMV, \quad (1)$$

where C is the divers consumption rate, D is the depth in feet of seawater (fsw) and RMV is the respiratory minute volume in units of actual cubic feet per minute. fsw is a common unit used in the diving community due to Navy Divers spending most of their dive time in sea water. Using the Respiratory Minute Volume of a moderate working diver found in figure 3-6 of [1] and a depth of 60fsw, the diver's consumption rate was calculated to be 3.95scfm, where scfm is standard cubic feet per minute. The available air capacity is then calculated using

$$V_a = \frac{P_c - P_m}{14.7} \times FV \times N, \quad (2)$$

where V_a is the available air capacity, P_c is the measured cylinder pressure in psig, P_m is the minimum pressure of the cylinder in psig, FV is the floodable volume in units of scf (standard cubic feet) and N is the number of cylinders. The minimum pressure of the cylinder is taken to be 500psig due to the requirements outlined for diving in [1]. For the aluminum 100 tank used in the experiment V_a is calculated to be 89.5scf. The duration, which is found by taking equation (2) and dividing it by equation (1) comes out to 23 minutes of bottom time. This time can vary depending on factors such as diver experience, surface and bottom temperature differential, and amount of air use of the buoyancy compensator.

According to [1], the minimum equipment required is Open-circuit SCUBA with submersible pressure gauge, life preserver/buoyancy compensator, weight (if required), dive knife, face mask, swim fins, submersible wrist watch, and a depth gauge.

SCUBA diving is followed in complexity by surface-supplied diving, allowing for an unlimited amount of air. This type of diving supplies air to the diver through a compressed air bank on a surface vessel. The vessel is equipped with compressors and has an unlimited supply of air. A restriction to this method is that the diver must be tethered to the vessel via a breathing hose and communication cable. The required equipment according to [1] is a KM-37 NS helmet, harness, weight belt (if required), dive knife, swim fins or boots, surface umbilical, and an EGS bottle deeper than 60fsw. Figure 2 shows students at the training pool at the Naval Dive and Salvage Training Center (NDSTC) wearing the required equipment for surface-supplied diving.



Figure 2. Two students in surface supplied diving required equipment. Students in yellow helmets are the divers while the two divers to their right are the dive tenders ensuring they enter the water without tangles, and they communicate commands from the dive supervisor.

The helmet worn during surface supplied diving operations is the KM-37. The helmet is dry on the inside assisting with thermal insulation.

2. Dive Suits

There are many styles of suits available to the consumer today. The most used suit is a neoprene wetsuit. Neoprene is a synthetic rubber which was developed by a Dupont scientist in 1930 [5]. Neoprene has been used since then due to its thermal insulative properties, flexibility, and ease of production.

The thickness of the wetsuit is the most variable factor in the wetsuit industry. Wetsuit thickness available on the market ranges from a 1mm skin suit to over 8mm. The thickness varies based on the activity being performed in the wetsuit. Triathletes and competitive swimmers typically wear the thinnest suits due to the need for mobility and the warmer surface water they are in. Their internal body temperature is also higher due to the strenuous activity they engage in. On the other hand, free divers and scuba divers commonly wear thicker suits due to the locations of their activities and the lower amount of body heat they generate during their pursuits. There are also other sports that require more mobility, such as surfing, where the wetsuit is designed to provide a thicker layer of neoprene in the chest and back area and thinner sections on the arms and legs. Surfing and body surfing involve nearly continuous movement, which raises the internal body temperature of the wearer, thus necessitating a thinner suit.

There are two common types of neoprene wetsuits available in the market: open-cell neoprene and closed-cell neoprene. Open-cell neoprene lacks a lining on the inside of the suit, whereas closed-cell neoprene has this lining, which facilitates the process of donning the suit. Although the open-cell suit is more challenging to put on, it offers the advantage of superior insulation. The sticky nature of the open-cell design results in a thinner layer of water forming between the wetsuit and the diver. However, a drawback of the open-cell design, aside from the difficulty in donning, is its susceptibility to rips and tears [6].

The last cold-water option used in the military is the hot water suit. This wetsuit features a hose through which the wearer continuously circulates hot water. The water temperature must be carefully monitored to ensure it remains warm but not too hot. However, the hot water suit has logistical challenges, such as obtaining a vessel capable of

providing hot water, and the diver becomes tethered to the vessel through the hose. This technique is most employed in surface-supplied diving, where the diver is already connected to the vessel via an air hose, making it highly effective for diving in extremely cold sea temperatures.

One significant drawback of a neoprene wetsuit is the compressibility of the material. As a diver descends in the water column, the neoprene material compresses. This compression not only reduces the material's thermal insulation but also affects the diver's buoyancy, necessitating a greater adjustment of force from the buoyancy control device (BCD).

C. BODY TEMPERATURE AND DIVING

Regulation of body temperature while diving is of utmost importance. The average body temperature is 98.6 degrees Fahrenheit [1]. A person at rest can maintain their core body temperature with no thermal protection in water that is 91 degrees Fahrenheit. The water on the west coast of the United States is rarely above 70 degrees due to the California current, which brings cold water down from the Gulf of Alaska. In Monterey, the water is frequently below 50 degrees Fahrenheit. The thermal conductivity of water is much higher than that of air, causing a diver to get colder faster in water than in air. In SI units, the thermal conductivity of air is 0.026, while in water, it is 0.6 (watts per meter per kelvin) [7]. Saltwater is 23 times more thermally conductive than air. Another factor to consider is thermal capacity. A higher thermal capacity requires more energy to heat up a material than a lower thermal capacity. The thermal capacity of liquid fresh water is 4.18 J/gK with salt water being just slightly lower and for room temperature air it is 1.01 J/gK [8]. It will take more energy from your body to heat up the surrounding water than it would to heat up the same amount of air. The combination of these factors results in significant thermal loss to the human body while diving. Another issue when working in cold waters is that the more a diver moves, the more water is pushed away from them, taking body heat along with it [1]. Hypothermia is a significant concern for divers in cold water, occurring when the body cannot produce the same amount of heat that the water is removing [1]. Figure 3 shows the symptoms associated with a decrease in core temperature. The lowest core temperature a

person can sustain is 79 degrees Fahrenheit before death. Figure 3 illustrates the relationship between core body temperature and medical symptoms.

Core Temperature		Symptoms
°F	°C	
98	37	Cold sensations, skin vasoconstriction, increased muscle tension, increased oxygen consumption
97	36	Sporadic shivering suppressed by voluntary movements, gross shivering in bouts, further increase in oxygen consumption, uncontrollable shivering
95	35	Voluntary tolerance limit in laboratory experiments, mental confusion, impairment of rational thought, possible drowning, decreased will to struggle
93	34	Loss of memory, speech impairment, sensory function impairment, motor performance impairment
91	33	Hallucinations, delusions, partial loss of consciousness, shivering impaired
90	32	Heart rhythm irregularities, motor performance grossly impaired
88	31	Shivering stopped, failure to recognize familiar people
86	30	Muscles rigid, no response to pain
84	29	Loss of consciousness
80	27	Ventricular fibrillation (ineffective heartbeat), muscles flaccid
79	26	Death

Figure 3. Symptoms related to the lower of the body's core temperature ranging from slightly low at 98 degrees to death at 79 degrees. Source: [1].

II. PRIOR WORK

A. HISTORY OF THE WETSUIT DESIGN

In 1973, a report from the Navy Clothing and Textile Research Unit (NCTRU) initially researched the use of a polyurethane, hollow-glass-microsphere composite and a polyvinylchloride, hollow-glass-microsphere composite [9]. NCTRU determined that the material was nearly incompressible down to 1000fsw and provided better insulation than the neoprene wetsuits of that time [9]. However, the concept was not further explored by NCTRU due to the constant breaking of the beads. Since then, manufacturing quality has significantly improved, allowing for the commercial availability of inexpensive, high-quality beads. The microspheres produced by 3M today can withstand a crush strength of 250 PSI [10]. According to the U.S. Navy Diving Manual 1PSI is equal to 2.25fsw [1]. The 3M K1 beads can withstand a depth of 562fsw. This advancement has enabled NPS to conduct further research on this topic.

In June of 2018, Jonathan Brown published his thesis exploring the thermal insulation of 8mm neoprene compared to a 43% bead volume composite. Figure 4 shows his findings.

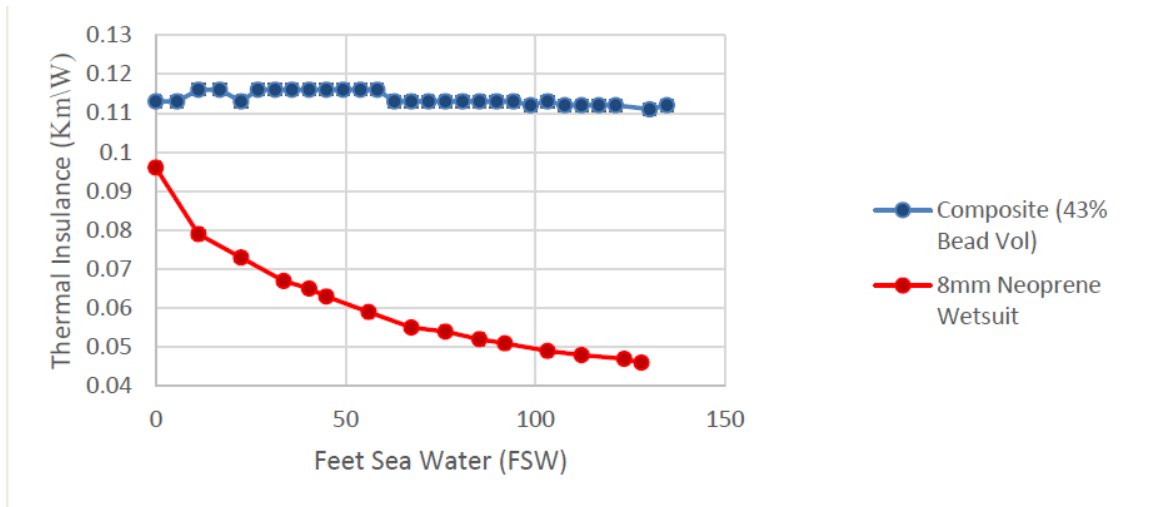


Figure 4. Thermal insulance versus feet of sea water for a 43% bead volume composite and an 8mm neoprene wetsuit. Source: [11].

The composite material is shown to maintain its thermal insulation through an increase in pressure, while the 8mm neoprene wetsuit significantly drops in thermal insulation as the pressure is increased. The greatest decrease in thermal insulation occurs with the first additional atmosphere. In sea water, 2 atm occurs at 33fsw. Brown also determined the optimal ratio of microsphere content to polydimethylsiloxane. Polydimethylsiloxane is a silicone polymer used to create hardened, rubber-like pads when mixed with microbeads and hardener. The polymer is necessary to shape the beads into a rigid structure. The optimal percentage of glass beads to polymer is 53% [11]. A higher percentage of beads resulted in an inhomogeneous mixture as well as a highly viscous mixture unable to be poured into a mold [11]. A lower percentage of beads would decrease the thermal efficiency of the mixture.

Once it was determined that this material would provide a better solution to diver protection, the fabrication and testing process began. The initial proof of concept was completed by students Shane Martin and Aaron Demers with the advisement from Dr. Kartalov. A 3D scan of Shane Martin was completed using an Occipital Structure Sensor Mark 1 imaging tool [12]. The full body scan was then converted into segmented pieces allowing for better mobility. Solidworks was then used to design a 3D mold for each piece to be cast. After the mold was designed, the mold was then printed using the NPS Fortus 400mc 3D printer [12]. The composite was then poured into the mold and pieces were cast. The pieces were sealed into a wetsuit and tested by Shane Martin. This original suit was named the “K” suit. His results from the diving tests are shown in Figure 5.

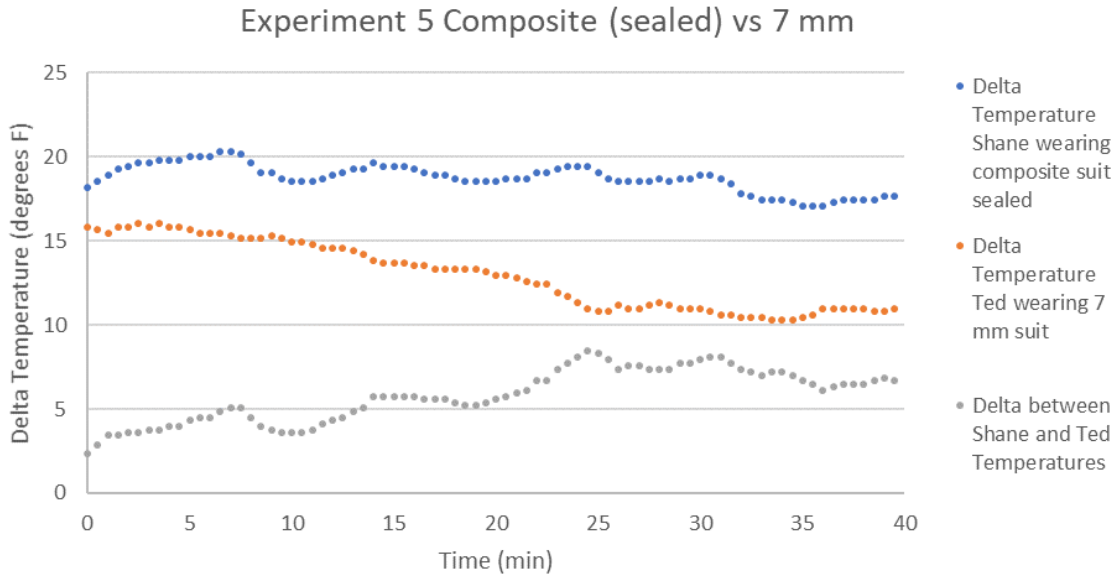


Figure 5. Experiment five from Shane Martin’s thesis shows the delta in temperatures from two divers, one wearing a 7mm suit and the other wearing a composite suit with sealed pieces. Source: [13].

While this design process proved effective, the implementation was highly specific to the individual. The manufacturing process would be too costly and time-consuming for widespread application. The manufacturing process was improved upon by Andrew Waldron. Waldron was able to design an improved technique incorporating the “choco-bar” method which allows for a wider application to differing body types and sizes. Figure 6 shows the “choco-bar” design.

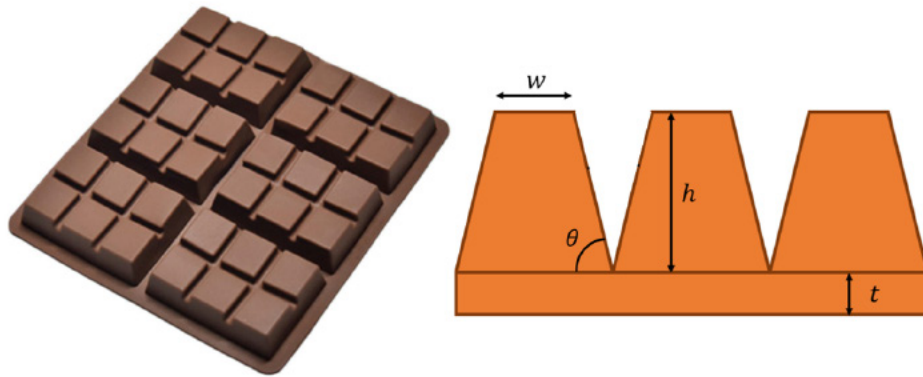


Figure 6. The brown colored mold on the left shows an example of what the final pieces will look like. The orange-colored picture on the right shows a cross section of the “choco-bar” design with w being the width of the inner surface, θ being the angle of curvature of the trapezoid, h being the height, and t being the thickness of the base. Source: [14]

This new method will allow manufacturers to easily customize suit pieces by cutting the pre-formed blocks to size. A cross section of how this “choco-bar” method is implemented is shown in Figure 7.

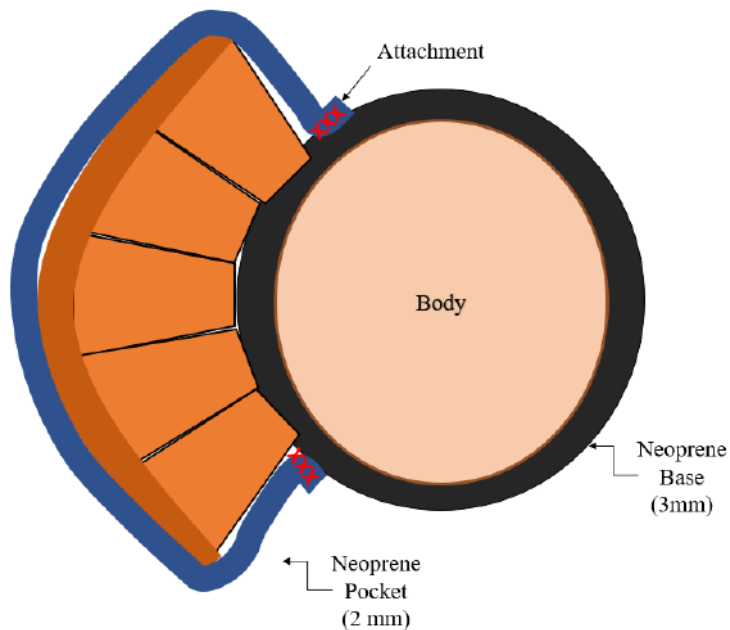


Figure 7. A cross section of how the “choco-bar” method is placed on the body. Source: [14]. The composite piece is shown in orange with a neoprene pocket shown in blue and a neoprene base shown in black.

Waldron created a dive suit using this method and tested it in the ocean, but the experiment was compromised due to a leak in the suit. The research was continued with Codi Clark. Clark’s suit consisted of a double layer of “choco-bar” composites with air-filled microspheres. Figure 8 illustrates how the double layer fits over a cardboard tube, simulating a body part.



Figure 8. The white pieces in the image are the composite pieces which are double stacked over a cardboard tube showing how the composite pieces will fit over a body part. Source: [15].

This suit was manufactured to a high standard and proved to be very effective in experimental testing. Figure 9 presents the results of a dive, comparing this suit to a commercially available 7/6mm neoprene wetsuit.

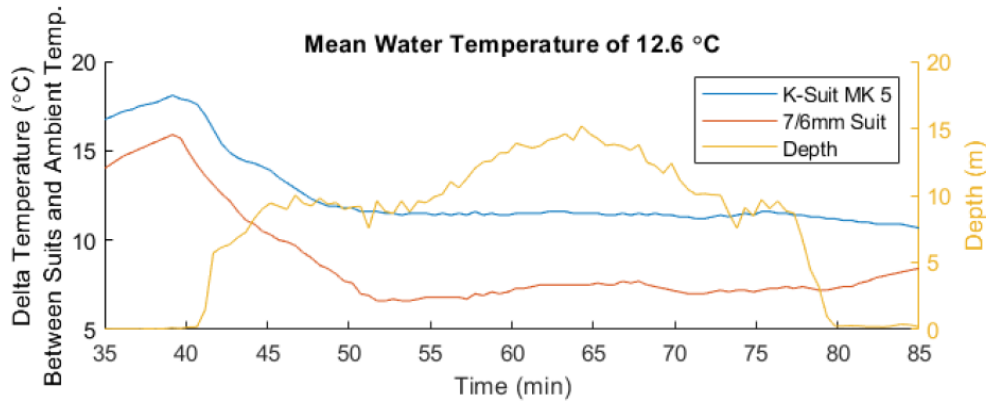


Figure 9. This image depicts a plot from Codi Clark’s thesis, illustrating the results of his first dive. Source: [16]. The composite suit’s delta temperature, indicating the difference between the ambient water and the interior of the suit, is represented in blue. In contrast, the delta temperature of the 7/6mm suit is depicted in red. Depth is measured in meters and is displayed in yellow.

These results showed that the K-suit MK 5 kept the diver warmer than a 7/6mm suit at depths of up to 15 meters. Although this suit proved effective thermally, the diver had to wear 30lbs of lead weight to maintain neutral buoyancy at depth [15]. This is about 10lbs more than what is typically worn when diving with a 7mm neoprene suit. This added weight makes getting in and out of the water very difficult. Another idea that was examined was the use of ceramic microspheres instead of glass to offset the need for added weight and to improve ergonomics.

Kostantinos Meligkaris examined the use of a glass bead composite layer adhered to a ceramic bead composite layer. The composite layers glued together are shown in Figure 10.

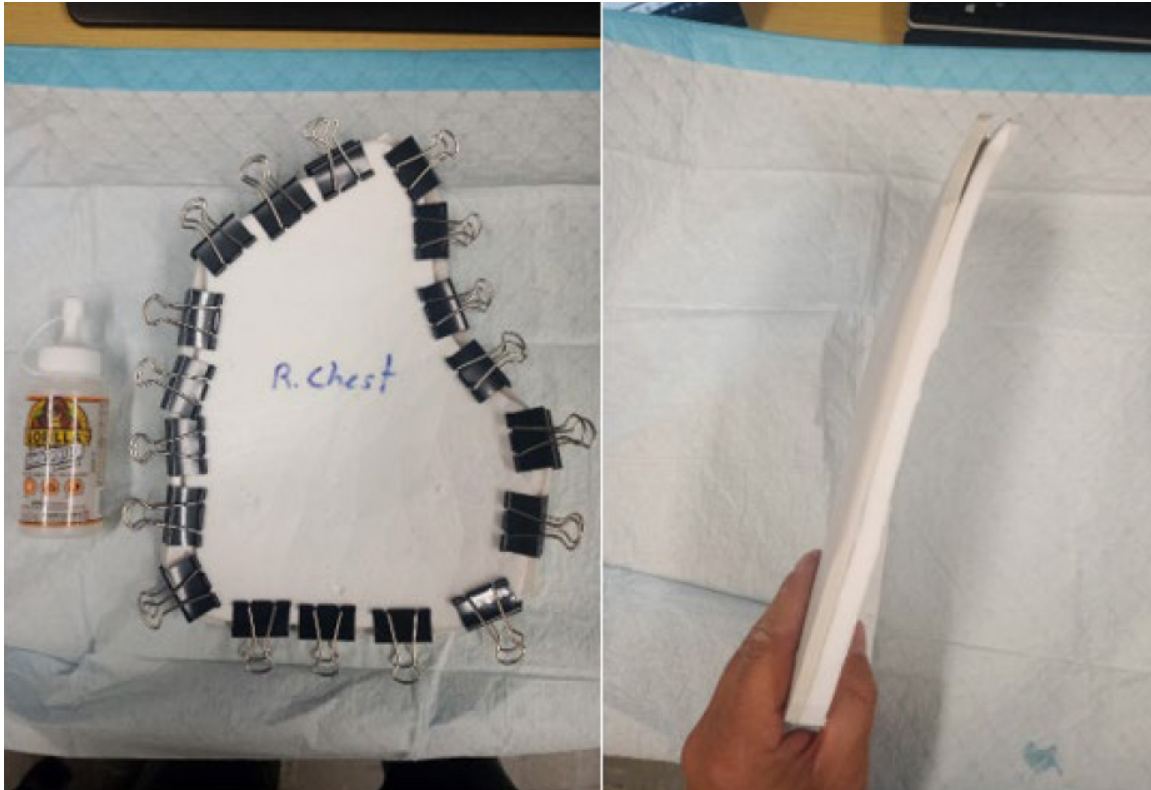


Figure 10. The picture on the left shows the two composite layers being glued together using clamps to hold the pieces together while the glue cures. The picture on the right shows the two composite pieces glued together.

Source: [16]. The white layer is composite with glass microspheres, the tan-colored layer contains ceramic microspheres.

This design was made into a wetsuit and the results proved that the suit beat the competing neoprene wetsuit for keeping the diver warm. Figure 11 shows the results of the K suit MK 4.

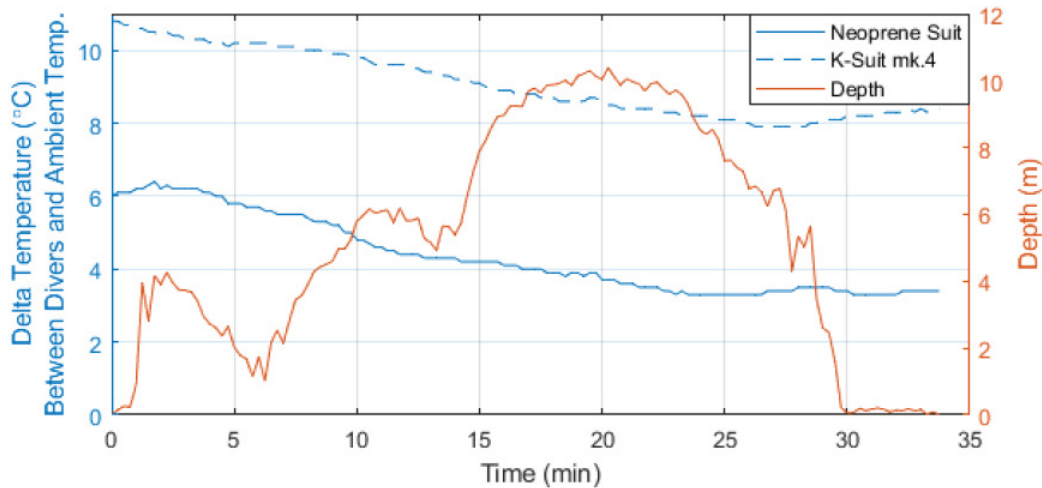


Figure 11. A plot of delta temperature between divers and sea water versus time. Source: [16]. The K-suit diver data is shown in the dotted line and the neoprene suit is shown in the solid blue line.

Although the MK-4 suit was effective, a manufacturing issue persisted, requiring individually tailored suits custom-made with each iteration. The next logical step in the research was to create a “choco-bar” designed suit with a mixture of ceramic bead composites and glass bead composites, combining the best features of the K suit MK 4 and the MK 5. This suit would be named the K-suit MK-6. Not only will the new suit benefit from the manufacturing improvements brought about by the “choco-bar” design, but it will also incorporate a composite and glass bead layered design to enhance ergonomics. Having a composite pad along with a glass bead pad would allow the weight to be distributed throughout the body of the diver while keeping the diver warm.

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III. MATERIALS AND METHODS

A. MANUFACTURING PROCESS

The procedure that was used during the fabrication process of this K-suit MK-6 was similar to the K-suit MK-5 and MK-4. Firstly, a two-part Sylgard 184 Polydimethylsiloxane (PDMS) was mixed using a 10:1 ratio of elastomer to curing agent in a 300 mL beaker [15]. The 3M K1 glass bubbles with a diameter of 65 microns [10] were added to the mixture at a 3:2 volumetric ratio [15]. There is some difference between pieces that were made due to the ability to accurately pour the elastomer, hardener, and beads from the containers into the beaker. The goal ratio was 90g of elastomer, 9g of hardener, and 10g of glass beads. The ratio for the ceramic beads was similar with the elastomer and hardener both still being 90g and 9g. The ceramic beads weigh much more and due to that, 120g of ceramic beads were added to the mixture. The beaker containing the mixture was then put in the lab's planetary centrifuge. This centrifuge was set to spin at 1500 revolutions per minute (RPM) for four minutes. The centrifuge was calibrated to adjust for the weight of the beaker inserted.

Once the four minutes was up, the beaker was then removed from the centrifuge and placed into the vacuum chamber. The mixture was in the vacuum chamber for 1.5hrs running continuously at a pressure of .013mbar. The vacuum chamber sped up the process of de-gassing the mixture. Once complete, the mixture was then transferred into the "choco-bar" mold. The mixture was transferred from the beaker to the mold using a popsicle stick due to its low cost and ease of disposal [15]. The mixture was then left for one additional hour open to the atmosphere to allow more air to escape the mixture. Figure 12 shows the difference mixtures that had an additional hour wait time and those that didn't.

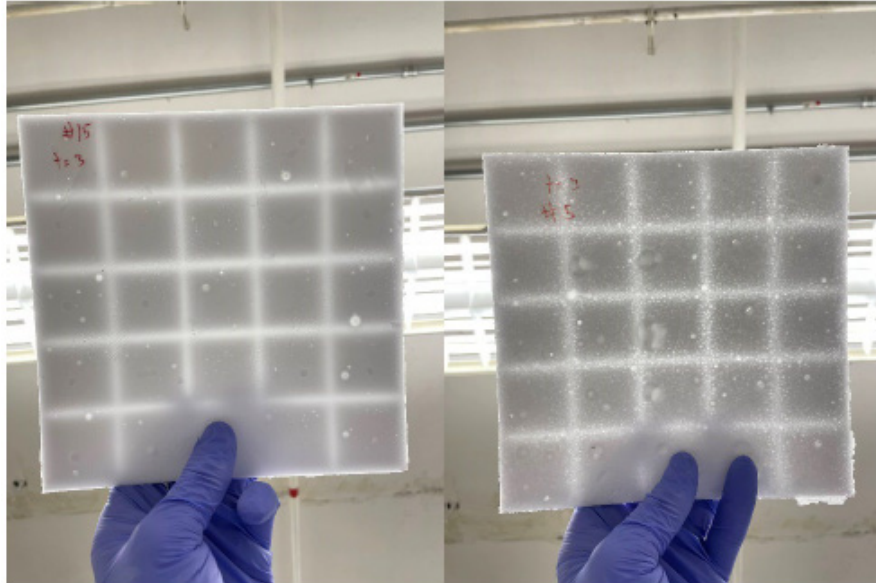


Figure 12. The left picture shows a piece that was created using an additional wait time of 1hr prior to placing in the oven. The picture to the right shows a mold that was not allowed the additional wait time. Source: [15].

As seen in Figure 12, there are more air bubbles in the mold that was not allowed the additional wait time. The additional air bubbles in the mold would add unwanted buoyancy as well as decrease the thermal properties. C-clamps were then applied to the corners of the mold with a 3mm covering over the top, to ensure even distribution of the mixture. Figure 13 shows the C-clamps applied to the mold.

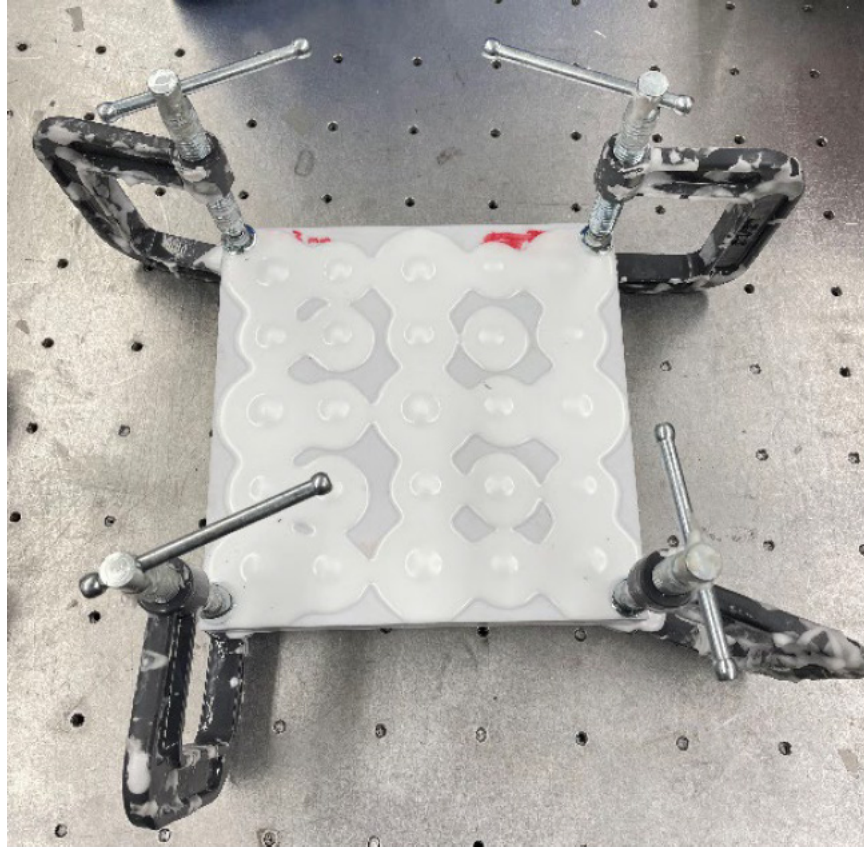


Figure 13. C-clamps are applied to the corners of the mold which allowed for even distribution of the mixture. Source: [15].

The mold was then placed in an 80-degree Celsius oven for 2 hours with the C-clamps still attached. The mixing beakers, as well as the petri dishes, were also placed in the oven to assist with cleanup. The hardening of the mixture was easier to clean off than a wet mixture. The oven was set with a timer so that it automatically turned off after the two hours had elapsed. This timer allowed the mixture to cool off, enabling us to remove the mold after it had cooled. Once the mold was out of the oven, the top cover and the bottom mold were removed using chisels. Figure 14 demonstrates how the use of chisels made the process easier.



Figure 14. Chisels are used to delicately remove the top piece from the bottom mold to maintain the integrity of the composite piece.
Source: [15].

Small air bubbles would still accumulate near the surface of the mold. These were later filled during the fabrication of the next composite by using left over mixture and re-baking. Once all the composites were made, it was time to fabricate the suit.

Suit fabrication began with the purchase of a custom 3mm wetsuit made by 7till8. This specific suit was designed with a detachable hood and a chest zip entry. The chest zipper, as opposed to a back zipper, allows for less water to enter through the zipper seam. The chest zipper is sealed by using an additional yoke piece that is pulled over the head and zipped to an additional flap on the chest of the suit. Sixteen measurements were taken of the body to ensure a proper fit [17]. These measurements were sent to the company electronically, and four weeks later, the wetsuit arrived. Once the wetsuit arrived, it was taken to Otter Bay Wetsuits to begin the installation of the composite pieces. Pockets were glued onto the wetsuit to house the composite pieces. The neoprene used to make the pockets was 2mm closed cell. Figure 15 illustrates one step of the fabrication process.



Figure 15. The neoprene wetsuit base is shown in grey. The black pieces are the pockets that are glued onto the wetsuit. The chest pieces were inserted through the diagonal cut in the pocket neoprene. The neoprene was then sewed back together using a baseball stitch and Aquaseal was then applied over the stitch to ensure a watertight seal.

All the pockets were attached using wetsuit cement. The composite piece was inserted simultaneously to ensure the proper form. Once the glue had dried and the pocket was in the correct position, Aquaseal was applied over the seams of the pockets to ensure a watertight connection. When trying on the suit, it was discovered that the legs and arms were too tight. Cricket from Otter Bay Wetsuits then added more wetsuit material to ensure

a proper fit. The helmet was constructed in a similar manner, with three pads glued to the neoprene in the same fashion. The helmet is shown in Figure 16.



Figure 16. The left picture shows a front view of the helmet. The picture on the right shows a side view of the helmet.

The helmet was constructed with three additional composite pieces on top because the wearer had to wear a mask while diving. The mask straps would need to be elongated if the pieces were to cover the ears and the back of the head. If composite pieces were designed to cover the ears, extra precautions would have to be taken to prevent outer ear squeeze. The wearer must be able to remove air from that region to maintain equilibrium.

IV. TESTING AND PERFORMANCE

A. DIVE 1

Dive 1 took place on October 24th, 2023, at San Carlos beach in Monterey California. This is a common spot for SCUBA divers to explore underwater due to the vast marine life in the area and the ease of access. Prior to the dive, biometric data was taken using the Smart Body Analyzer by Fitindex. The model used was ES-26M. The data was taken prior to each dive. Figure 17 shows the biometric data taken for the diver wearing the composite K suit, Garrett, and the second diver, Alan, wearing the 7mm neoprene suit during test 1.

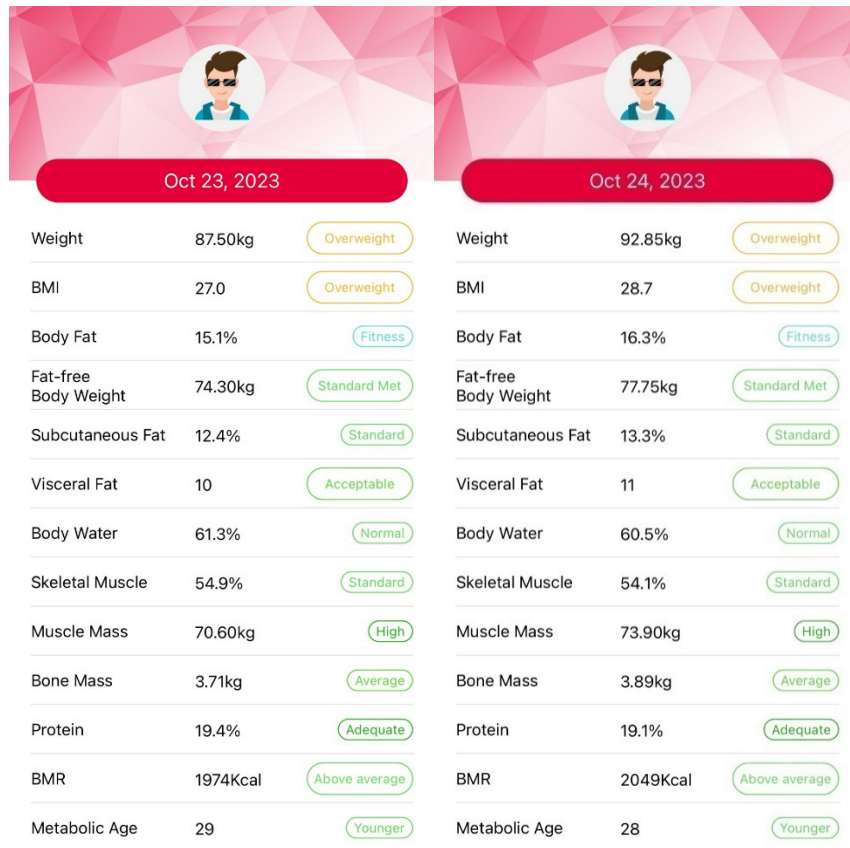


Figure 17. The left image shows the biometric data of Garrett, the diver in the composite K suit. The right image shows the biometric data of Alan, the diver in the control 7mm neoprene wetsuit.

Both measurements were taken in athlete mode, as recommended by the application connected to the Fitindex scale via Bluetooth. The criteria required to use athlete mode are that the user is 18 or older, engages in more than 6 hours of intense aerobic activity per week, and has a resting heart rate below 60 bpm [18].

As the diver wearing the composite suit was donning the suit, a seam in the arm ripped, creating a hole approximately the size of a quarter on the left arm. This issue was temporarily remedied by using duct tape to patch the hole. It was also found out after the dive that some of the seams weren't sealed with Aquaseal causing more of a leakage issue. Some water managed to enter the suit, compromising the data. Temperature and pressure were measured using an Omega OM-CP-PRTEMP140 high-temperature and pressure data logger, which was positioned in the center of the chest. Figure 18 shows the results of the dive.

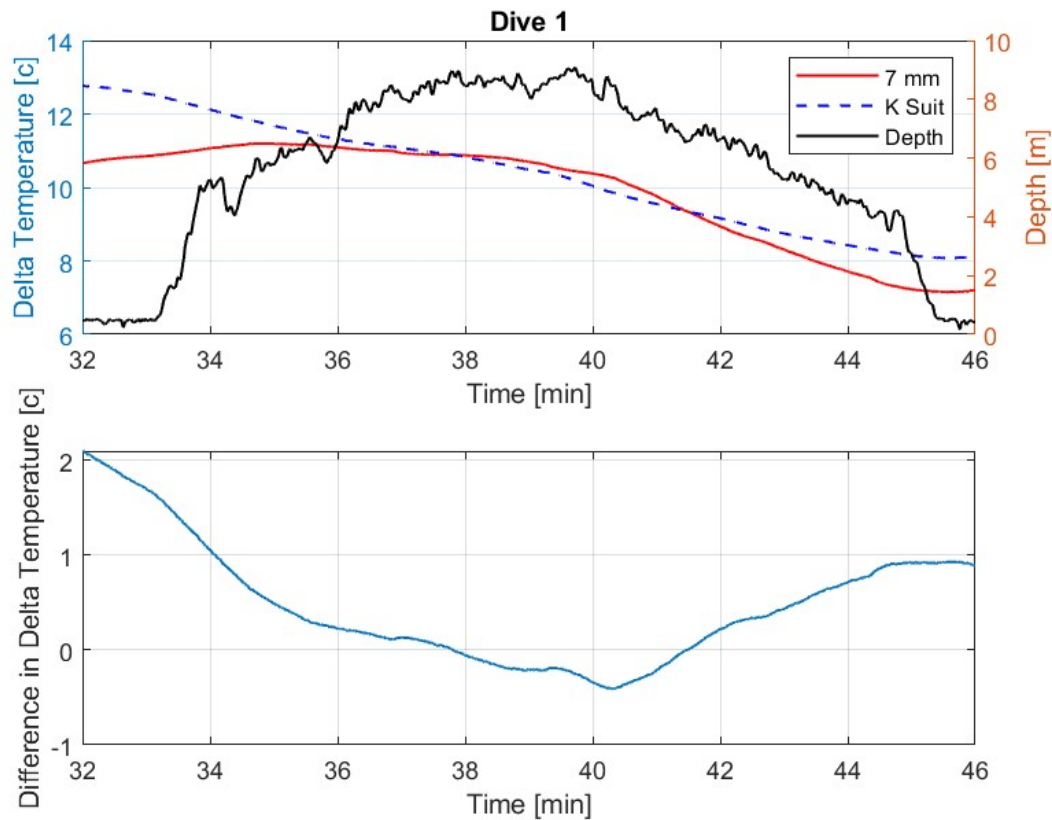


Figure 18. The top plot displays the temperature difference inside the 7mm suit and outside the suit in red, the temperature difference of the composite suit in blue, and the pressure in black. The temperature difference was recorded using an ambient pressure sensor located outside the suit, attached to the BCD. The left axis represents temperature measured in Celsius, while the right axis represents depth measured in meters. The bottom plot illustrates the temperature difference between the divers.

As observed in Figure 18, the K suit maintains a higher temperature for most of the dive. The K suit exhibits a maximum temperature difference between the divers of 2 degrees Celsius at the beginning of the dive, prior to descending to greater depths. This measurement represents the variance between the lines plotted in the top image of Figure 18, specifically between the blue dotted line and the red line—the delta-delta temperature difference between the divers’ suits. This difference serves to illustrate how much warmer the K-suit is. The pressure sensor measures pressure in bars. According to [1], 1 bar of pressure is equivalent to 32.6336fsw. This conversion was applied to convert the pressure

readings from bars to feet of sea water and subsequently to meters. For the first dive, the pressure and temperature sensors were set to record data every second. In subsequent dives, this interval was extended to every 10 seconds. MATLAB was utilized for these conversions and data visualization.

In this dive, the diver wore an Xcel Hydro Flex 7.6 neoprene wetsuit. The wetsuit features a 7mm thickness in the chest and back and 6mm in the arms and legs, providing increased mobility. Notably, this wetsuit did not have an integrated hood; instead, the diver wore a separate hood that tucked into the wetsuit.

B. DIVE 2

Dive 2 took place on October 25th at the same location as the first dive: San Carlos Beach in Monterey, California. For this dive, the composite wetsuit had undergone a repair to address the issue of water leaking through a hole in the arm. The repair simply involved sewing the neoprene together, as there was insufficient time between dives to apply an aqua seal. Consequently, the wetsuit still experienced some water leakage into the arm. The stitching is done in a way that prevents full penetration of the neoprene with the needle, reducing the number of holes and minimizing water entry. Figure 19 depicts the process of patching a hole in the arm.



Figure 19. A depiction of how the neoprene is stitched together to patch the hole in the arm. The grey color represents the 3mm neoprene suit, while the black corresponds to the outer covering of the pockets that contain the composite pieces. This photo was taken at Otter Bay Wetsuits, with the shop cat visible in the background.

The biometric data was taken in the same manner as dive one, prior to the dive. Figure 20 shows the biometric data for both divers.

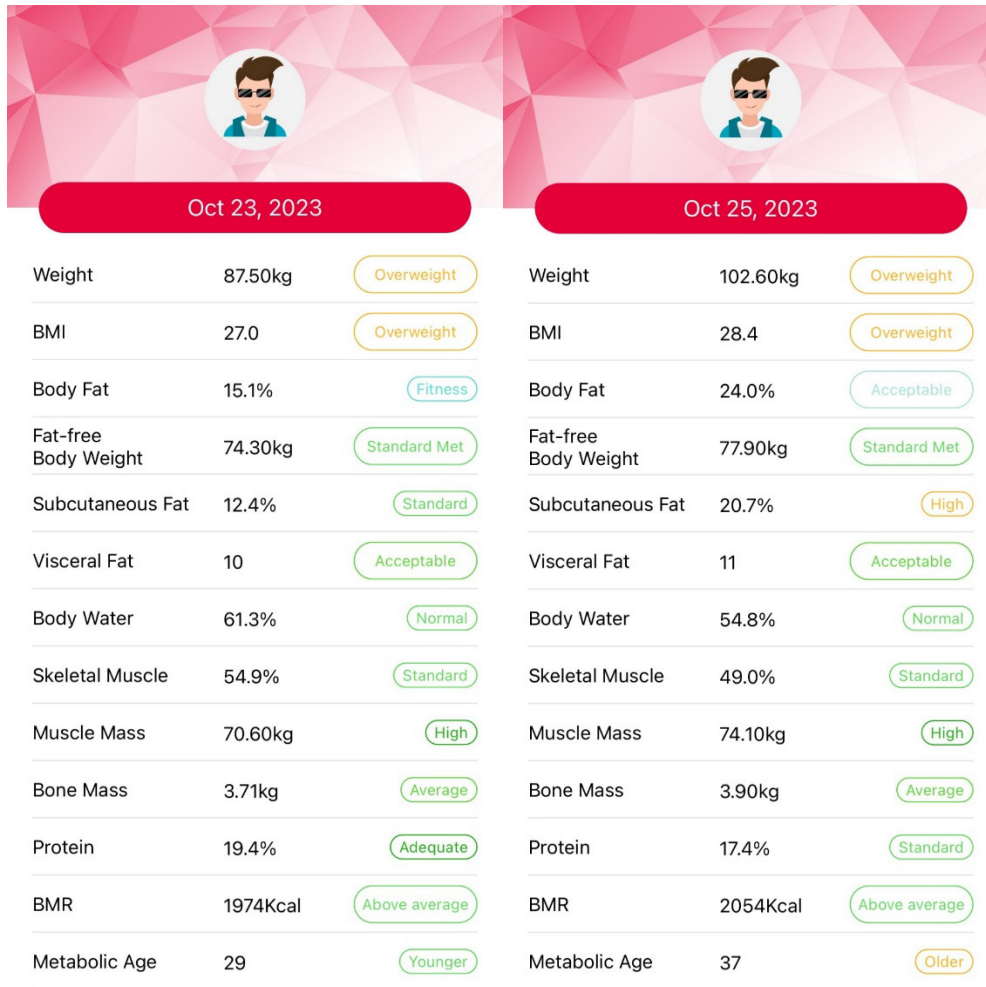


Figure 20. The left picture features the same diver, Garrett, while the right picture shows diver Kyle. The biometric data for Garrett on the left is the same as in the first dive, provided here for comparison.

Kyle wore a double-layered 7mm neoprene wetsuit. The suit consists of a Farmer John-style overall that sits beneath a 7mm jacket. The thickness in the chest and back is 14mm due to the double layer of protection. This double layer of neoprene provided supreme thermal protection. Figure 21 shows the results of dive 2.

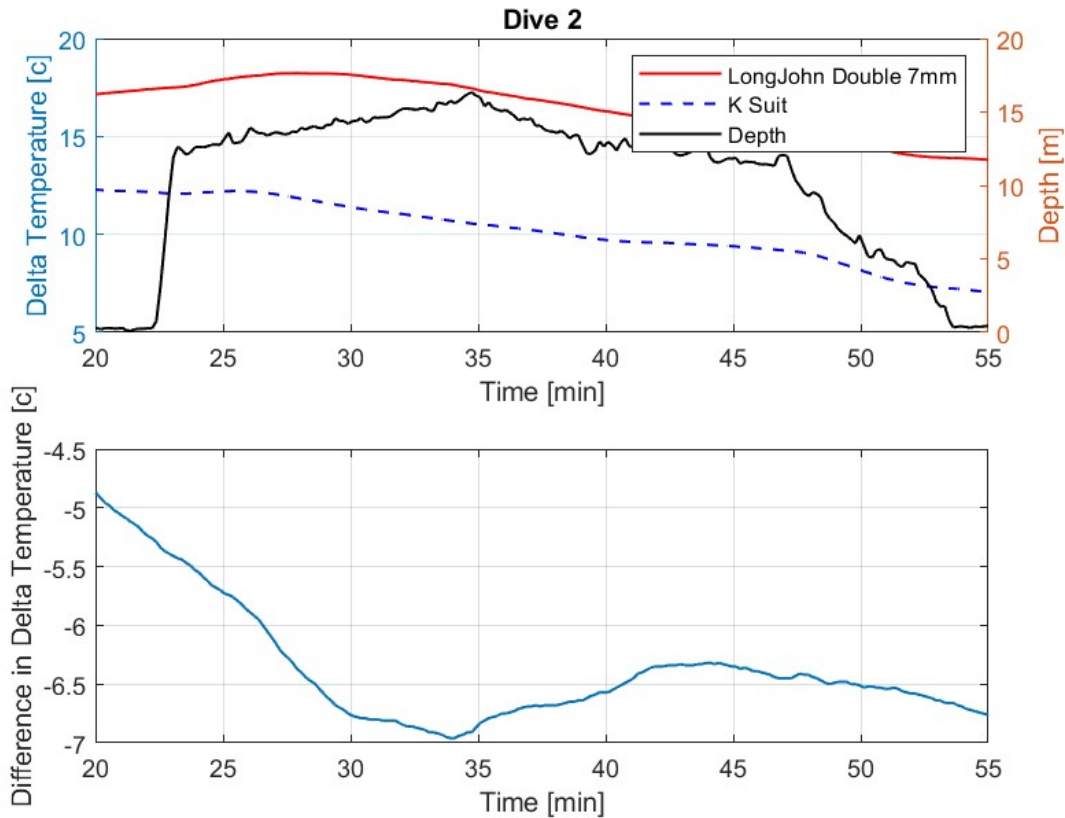


Figure 21. The plot above displays the long john suit in red and the K suit in a dotted blue line. The plotted temperature represents the difference between the inside of the suits and an ambient pressure and temperature sensor placed in the BCD during the dive. The pressure, indicated in black, is measured in units of depth in meters. The plot below illustrates the temperature difference between the long john suit and the K suit.

The long john suit keeps the diver warmer during the dive but sacrifices some degree of ergonomics. The difference in temperatures starts at 4 degrees Celsius, and once in the water, it slightly improves to a 3-degree difference. As the dive progresses, the temperature difference increases to a 7-degree advantage in favor of the long john-style wetsuit. In contrast, the K suit exhibits a slight decline in temperature throughout the dive. This is partially attributed to the suit not being properly sealed. It was sewn but not aqua-sealed prior to dive 2, allowing some water to seep in through the seams.

C. DIVE 3

Dive 3 took place on October 27th at the same location as the first two dives, San Carlos Beach in Monterey, California. The K suit had been repaired prior to this dive, with the seams where the tears occurred on the arms being aqua-sealed. The biometric data for the two divers is presented in Figure 22.

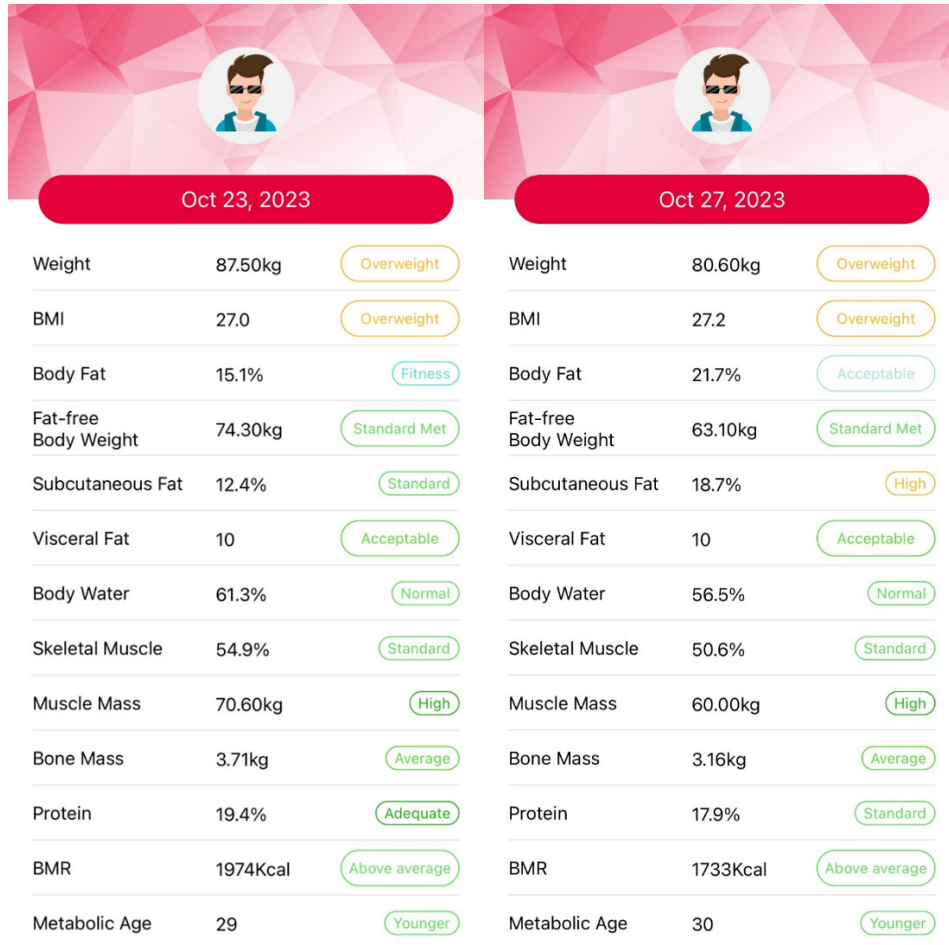


Figure 22. The left image shows the biometric data from the diver wearing the K suit, Garrett. This is the same biometric data that is used in the previous two dives. The image on the right shows the biometric data of the diver wearing a 7/5mm neoprene wetsuit.

Chris was wearing a SCUBA pro Everflex 7/5mm wetsuit. This wetsuit was 7mm in the chest and 5mm in the arms and legs. The results of the dive are shown in Figure 23.

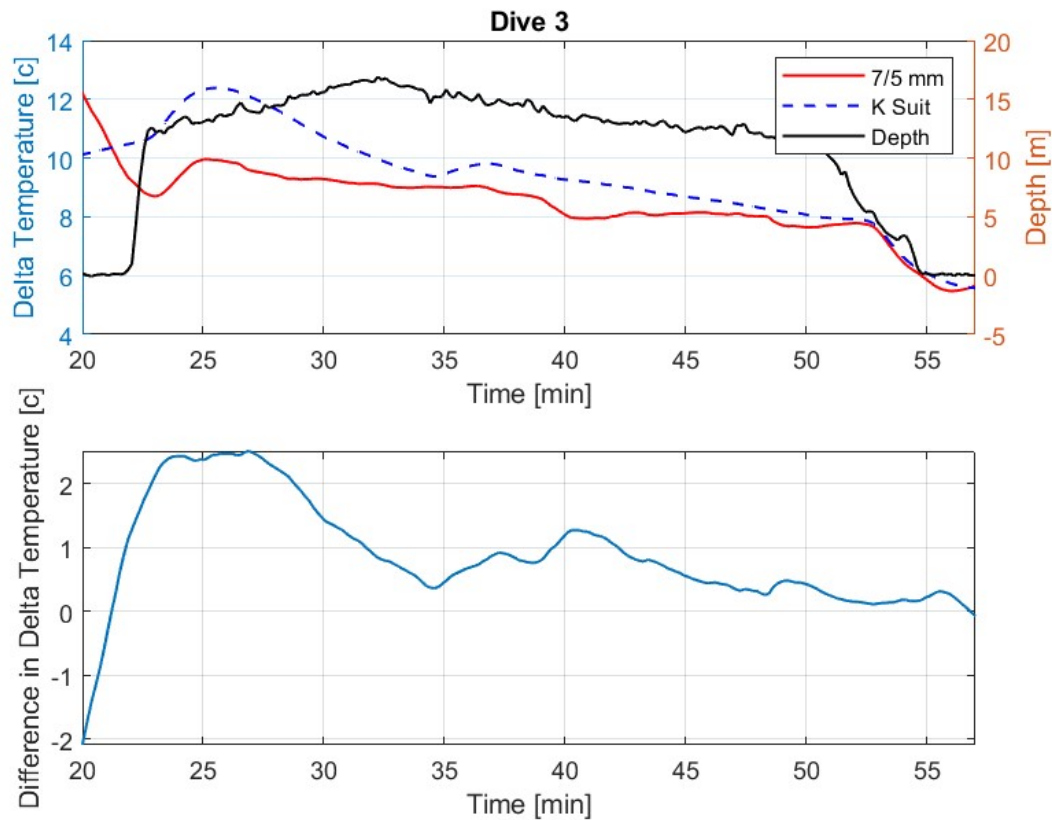


Figure 22. The plot above displays the temperature of the diver wearing the 7/5mm wetsuit in red and the diver wearing the K suit in a dotted blue line, while depth is represented in black. The plot below illustrates the temperature difference between the two suits.

In dive three, the K suit consistently outperformed the 7/5mm wetsuit throughout the entire dive. The maximum delta-delta temperature difference, slightly above 2 degrees Celsius, is depicted in the bottom image of Figure 23 and occurred just after the diver reached depth. This difference is represented by the variance between the blue dotted line and the red line, as displayed in the top image of Figure 23. It's interesting to note that the diver wearing the 7/5mm wetsuit started off significantly warmer than the diver wearing the K suit, which suggests that the K suit provides better thermal protection at depth, aligning with my initial hypothesis.

A point of concern is the fact that the temperature measured in the K suit declined throughout the dive. Subsequent inspection revealed that some portions of the seams were not properly aqua-sealed, indicating a possible small leak.

D. DIVE 4

Dive 4 was conducted on the 9th of November 2023 with the same subjects as Dive 3. Figure 22 shows the biometric data for the two divers. The diver wearing the 7/5mm wetsuit, Chris, wore the same wetsuit he used for Dive 3, and the only modification to the K-suit between dives was the application of aqua-seal to areas that had insufficient coverage. Figure 24 shows the data collected from dive 4.

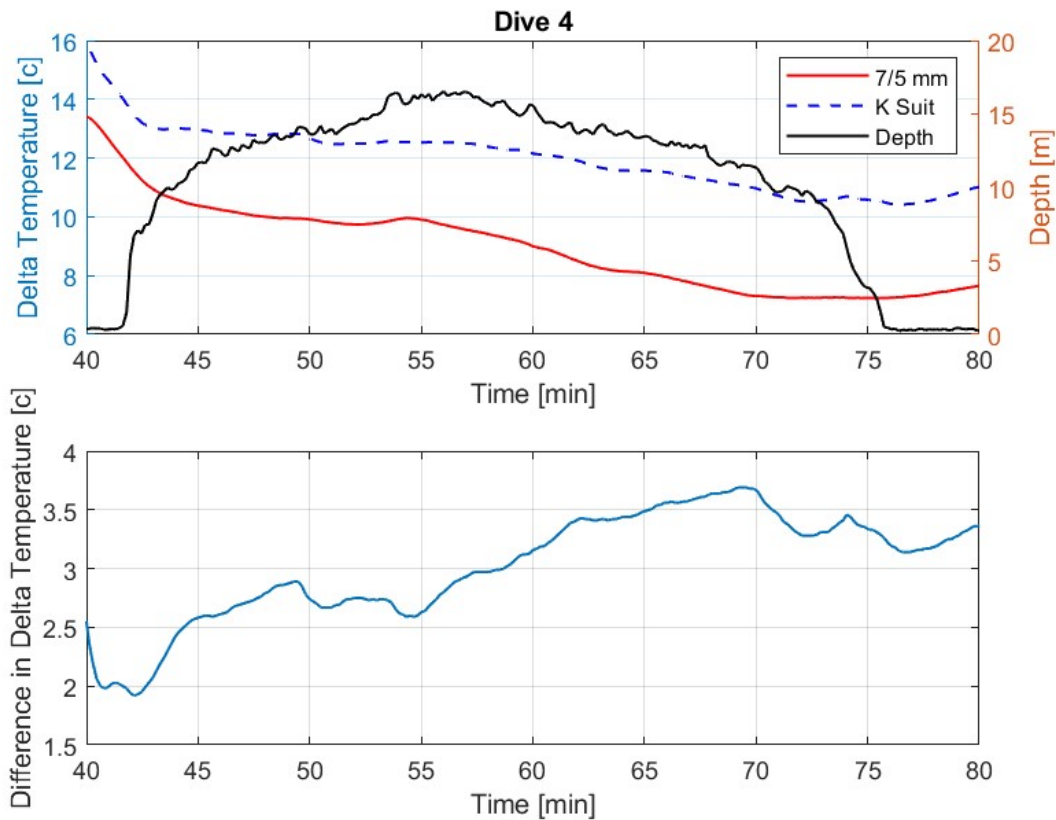


Figure 23. In the above graph, the y-axis on the left represents the temperature difference between the divers and the ambient water temperature. The axis on the right indicates pressure measured in meters of depth. The individual wearing the 7/5mm neoprene wetsuit is depicted in red, while the K-suit is represented by a dashed blue line. The following plot illustrates the temperature disparity between the two individuals, as derived from the above graph.

Figure 24 depicts an improvement in the thermal properties of the K-suit. The K-suit's temperature and pressure reader maintains a higher temperature than in Dive 3, while the 7/5mm wetsuit performs similarly, with a slight decrease in performance toward the end of the dive. Dive 4 was slightly longer than Dive 3. The only change made to the K-suit from Dive 3 to Dive 4 is the addition of more aqua-seal.

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V. CONCLUSION

A. PERFORMANCE

The K suit consistently outperforms both the 7/6mm wetsuit and the 7/5mm wetsuit. It exhibits less dependence on depth and a flatter response, as depicted in Figure 24. The advantage of the K suit becomes more pronounced with increasing depth and duration underwater, as illustrated in Figure 24. At depths between times 50 and 65 minutes, the mean temperature difference is 3.12 degrees Celsius warmer in the K suit. This value is slightly cooler than what was observed in [15], which reported around 4–4.5 degrees Celsius warmer temperatures at depth. This difference is attributed to the previous suit having a double layer of glass beads instead of a layer of glass beads along with a layer of ceramic beads, highlighting the superior thermal properties of glass beads over ceramics, as expected.

Another crucial factor influencing the wetsuit's performance is its ergonomics. Thanks to the distribution of ceramic pads throughout the wetsuit, weight is more evenly dispersed, improving ergonomics. Although 13 lbs of weight is still required to maintain proper buoyancy at depth, this demand is lower than what is typically necessary for a 7mm wetsuit under similar conditions. Figure 24 visually showcases the diver wearing the K suit while traveling underwater.g



Figure 24. The diver shown is wearing the K suit. The pouches containing the composite pieces are depicted in black, while the base layer of 3mm neoprene is shown in grey. The helmet can be observed in the far-right portion of the picture, rendered in black.

Ease of movement underwater, especially in the lower body, was much better than with any wetsuit thicker than 3mm. It felt as if I were wearing a full 3mm wetsuit, and the ease of kicking was unparalleled. The pads did not feel bulky or inhibiting in any way on the legs underwater. The chest and back pads were the same, with no impediments to motion in any way.

An issue with this iteration of the K-suit is that when it was fabricated, the patches designed for the humerus part of the arm were too long, impeding arm movement. This occurred because these patches rubbed against the forearm patches, restricting the arm's range of motion.

One downside to the K-suit is the time it takes to put it on. It was challenging to take on and off due to the weight of the suit. The process was also hindered by the effort

required to pass the hands and feet through the ankle and forearm pads. During manufacturing, additional wetsuit material was added to those regions because, initially, there wasn't enough space to maneuver the hands and feet through. The added material was 3mm neoprene, but it didn't maintain the same stretch as the rest of the suit. This issue could be addressed by either incorporating zippers or using a cylinder to stretch the suit at the ankles and forearms. This way, when the patches are glued on, they allow for more stretching.

The incorporated helmet did not restrict movement and provided warmth. However, there was some slight discomfort when the helmet was worn for long periods of time. This could be improved with more padding between the composite pieces and the 3mm neoprene.

B. FUTURE TESTING

Future testing not yet explored could include looking into how the K-suit protects against underwater shock or abrasions. Sharks are commonly found in the waters near Monterey and if there is a wetsuit that protects against shark bites, it would be beneficial to military divers and civilian divers in areas that hold this threat. Along the same lines, ballistic protection could be studied as well. There may need to be some material changes made to incorporate this advancement.

Another factor not considered that could enhance thermal protection involves utilizing a single large flat plate composed of glass or ceramic microsphere composites to cover the entire chest and back. This approach would not compromise ergonomics but would contribute to improved thermal protection.

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