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DEPTH INDEPENDENT THERMAL INSULATION FOR DIVING SUITS

by

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Our objective is to construct a depth-independent, full-body wetsuit that insulates the human body effectively regardless of the temperature of the ambient seawater to facilitate safer and more efficient swimming, diving, and underwater operations. To do so, we produced 3D scans of the human body, segmented the scans through the use of software to maximize ergonomics, and then converted the segments into digital mold patterns, which were 3D printed in polycarbonate. The molds were used to cast a composite consisting of hard hollow microspheres embedded in thermally cured carrier silicone elastomer. The composite casts were tested for ergonomic mobility and adjusted as needed. We also devised a method to attach the composite components to a commercial neoprene suit to be used as a waterproof bodyglove carrier, thereby producing the new segmented diver suit. Future work will assemble the full suit and test it under field conditions.

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DEPTH INDEPENDENT THERMAL INSULATION FOR DIVING SUITS

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Our objective is to construct a depth-independent, full-body wetsuit that insulates the human body effectively regardless of the temperature of the ambient seawater to facilitate safer and more efficient swimming, diving, and underwater operations. To do so, we produced 3D scans of the human body, segmented the scans through the use of software to maximize ergonomics, and then converted the segments into digital mold patterns, which were 3D printed in polycarbonate. The molds were used to cast a composite consisting of hard hollow microspheres embedded in thermally cured carrier silicone elastomer. The composite casts were tested for ergonomic mobility and adjusted as needed. We also devised a method to attach the composite components to a commercial neoprene suit to be used as a waterproof bodyglove carrier, thereby producing the new segmented diver suit. Future work will assemble the full suit and test it under field conditions.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three-dimensional
BCD	Buoyancy Control Device
CAD	Computer Aided Design
EDO	Engineering Duty Officer
EOD	Explosive Ordnance Disposal
FSW	Feet Sea Water
kg	kilogram
lbs	Pounds weight
mL	milliliters
ND	Navy Diver
NEDU	Navy Experimental Diving Unit
NMRI	Naval Medical Research Institute
NPS	Naval Postgraduate School
PC	Polycarbonate
PDMS	Polydimethylsiloxane
PSI	Pounds per square inch
rpm	Rotations per minute
SEAL	Sea, Air, and Land special warfare
STL	Stereo-lithography
UDT	Underwater Demolition Team
USD	United States Dollar

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Finally, I would like to thank my family for their endless support. Their love and patience has inspired me to be the best naval officer, student, and son I can be.

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I. INTRODUCTION

A. BACKGROUND

The human relationship with underwater diving is as old as it is intricate. Many ancient peoples dove as a means to gather food. Others dove to find valuable pearls and corals used in jewelry, commerce, and ancient medicines [1]. It was not until the Greek civilizations of the 8th century BCE that diving took on more commercial purposes. Hellenistic culture at the time utilized sea sponges as a device to aid in the elaborate Greek bathing process. As such, diving was required in order to harvest the sponges from the shallow inland waters of the Mediterranean Sea for sale at local markets. Curiously, it was this practice that led to new purposes for diving. As more sailing vessels ventured further from shore in search of sponges, many succumbed to the rougher seas and sank (often with hundreds of sponges on board). This created the need for “salvage diving.” Experienced divers with impressive lung capacity would swim down to these wrecks to salvage what they could from the cargo [1].

The earliest known military applications of diving are from the Peloponnesian Wars (431-404 BCE). Greek divers were used to swim under blockades of enemy ships in order to relay messages from port cities to Greek naval vessels of the coast. Additionally, these divers were used to inspect the hull thicknesses of enemy vessels and sometimes drilled holes in them as a form of sabotage [1].

In the years since the civilizations of Ancient Greece, diving has expanded along with the technology it employs in order to allow divers more time at greater depths. Modern divers perform a multitude of operations from ship repair, to harvesting bottom-dwelling food sources.

1. Military Applications

While it was a commercial need that created a need for diving, militaries of the world have greatly expanded the purposes diving serves. Modern militaries employ highly trained divers for a multitude of missions including underwater demolition, ship construction/repair, and underwater engineering [2]. Following the development of submarines in World War I, military diving took on a new and challenging role of submarine rescue, as many submarines sank with survivors trapped within their watertight compartments.

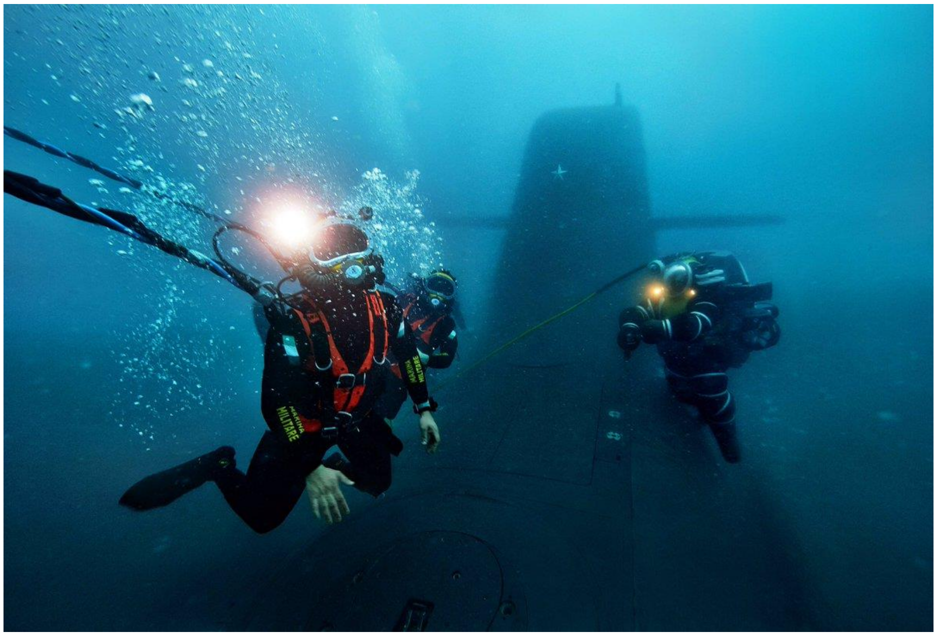


Figure 1. Navy divers approach submerged submarine. Source: [30].

2. U.S. Naval Applications

The U.S. Navy employs divers within the Engineering Duty Officer (EDO), Civil Engineering, Medical Officer, Explosive Ordnance Disposal (EOD), and Enlisted Navy Diver (ND) communities. Navy divers are qualified to perform a multitude of diving tasks and undergo extensive training to ensure fitness and competency [3].

Navy divers (of the above communities) conduct repairs on ships and submarines, perform salvage operations, remove/defuse underwater mines, and conduct discreet underwater personnel insertions near high value targets. Due to their often high-risk assignments, the technology associated with Navy diving has seen consistent improvement over recent years.

Early Navy divers employed much of the same dated techniques and technology of their ancient Greek counterparts. It was not until the early 20th century that naval diving technology began to improve markedly. Early U.S. submarine technology was limited, and a series of mishaps occurred resulting in the sinking of several of these submarines [4]. In the early 1900s, divers lacked the ability to go much further than 60FSW. It was not until 1912, when Navy Chief George Stillson pioneered an effort to test and employ a series of diving tables, which allowed divers to accurately estimate decompression times. This led to the ability for Navy divers to go to greater depths without as much concern for issues such as decompression sickness [5]. Navy diving technology continued to improve, and benefited greatly from the opening of the Navy Diving School in Newport, Rhode Island, just prior to WWI.

Plagued by reoccurring submarine sinkings (often with crews trapped inside), the Navy sought an apparatus which would allow sailors trapped aboard submarines to safely escape from their sunken vessels. Their solution came from Charles Bowers Momsen, a naval officer and graduate of the U.S. Naval Academy. In 1930 Momsen began working on a device to allow sailors trapped aboard sunken submarines to escape. His device, now referred to as the “Momsen Lung,” was essentially a rubber bag containing a mixture of lime and soda water, designed to remove toxic carbon dioxide from exhalations and recycle it into oxygen [4]. The device was slowly improved upon over the coming years, and saw many successful tests. However, when the U.S. Submarine Squalus sank in May 1939 in 243FSW off the coast of New Hampshire, the Momsen Lung saw its unplanned usage. Thirty-three Sailors survived the sinking and were rescued by a team led by Momsen himself, using the Momsen Lung to escape safely [4].

Figure 2. Sailor wears Momsen lung during test of apparatus.
Source: [11].

During World War II, an increase in the use of sea mines created a new problem for the U.S. Navy. Naval Vessels often struggled to detect and avoid the submerged mines, and it led to the sinking of numerous ships. The Navy quickly developed a team of specialists to defuse and remove these submerged hazards. This team was called the Underwater Demolition Team (UDT). Shortly after the development of the UDT, the Navy directed further specialization within the teams, splitting them into Explosive Ordnance Disposal (EOD) and Sea, Air, and Land (SEALs) units. These teams of specialists represented (and still represent) the elite men and women of the U.S. Navy specially trained for difficult diving operations (among other challenging operations).

Established in 1927, the Navy Experimental Diving Unit (NEDU) has long been the Navy’s lead source of dive testing, improvement, and innovation. Today, several other

Naval units exist to supplement NEDU's innovation and experimentation including the Naval Medical Research Institute (NMRI). These institutions currently serve to develop and improve Naval diving techniques and technologies [27].

Figure 3. Naval Experimental Diving Unit (NEDU). Source: [27].

Facilities like NEDU and NMRI are pivotal to address the continuing challenges of deep water diving. While much improvement has been made to diving equipment and technology, there is many unsolved issues that limit the abilities of naval divers even today.

B. CURRENT CHALLENGES AND POTENTIAL SOLUTIONS

The ocean, beautiful as it may be, is a less than hospitable place to be. Numerous forces place divers in precarious situations and must be carefully mitigated. From relentless ocean currents, capable of sweeping away even the strongest swimmers, to immense pressures and harsh temperatures faced at depth, there is always something to be aware of when conducting diving operations.

While the surface of the ocean is often warm and inviting thanks to warming from the sun, the temperature rapidly declines with depth. The thermocline is a region of the ocean beneath the surface where the decline in temperature happens most rapidly. In some cases, there can be more than one thermocline. Most thermoclines range from 660 FSW to 3000 FSW in depth. Dives within or beneath the thermocline are at the highest risk for detrimentally low temperatures [14]. Nearly all Navy dives are within or beneath the thermocline, due to the relatively small nature of the surface layer.

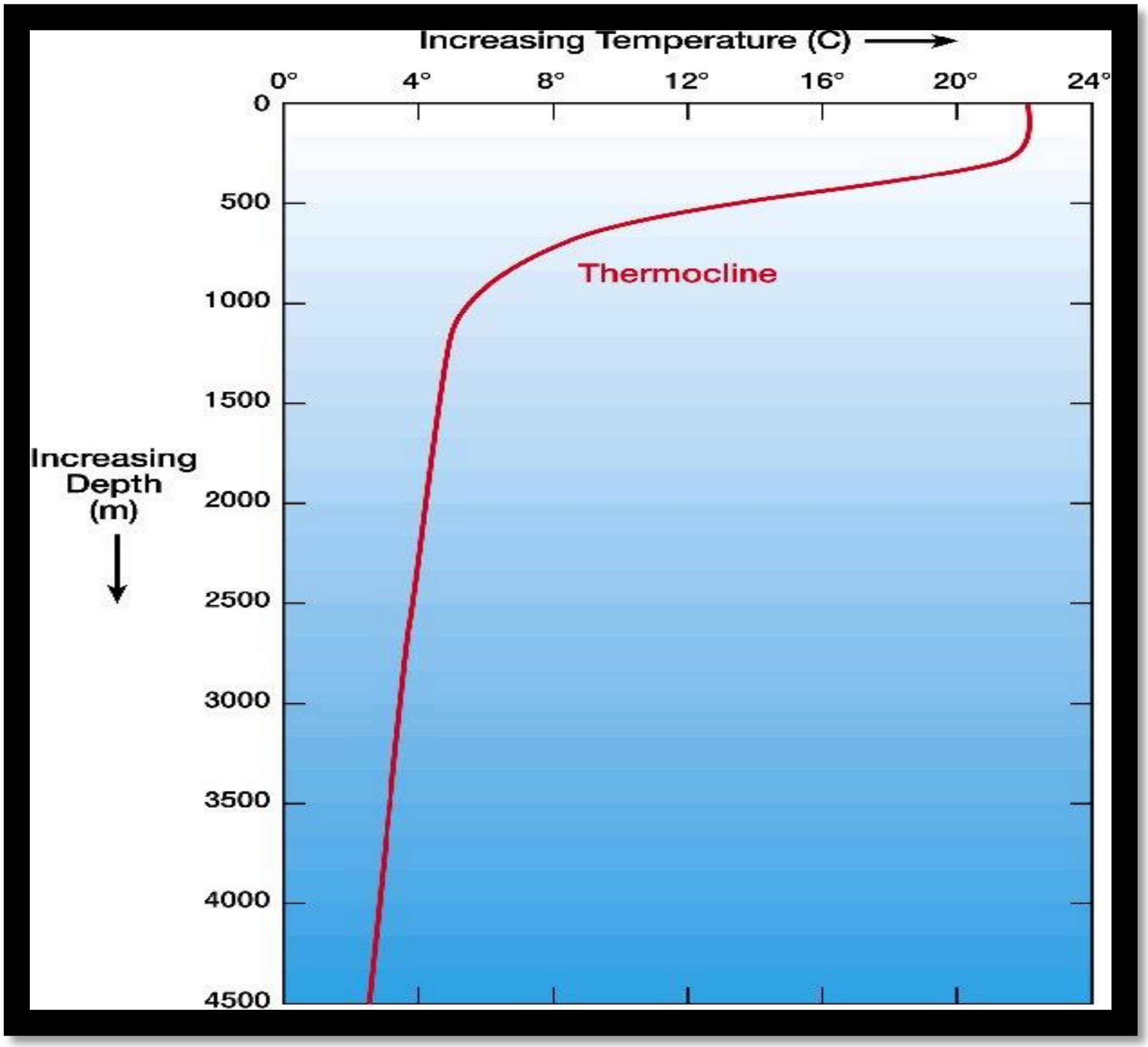
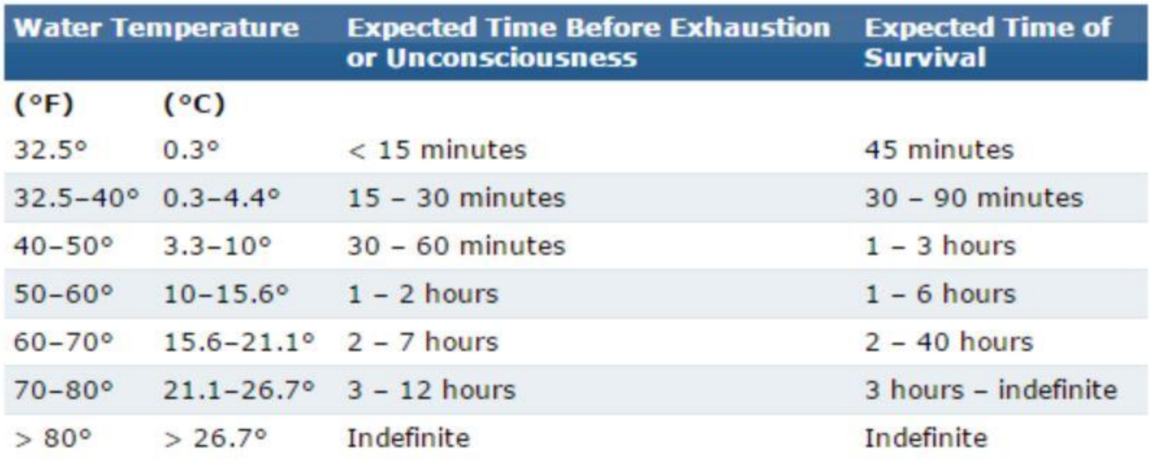


Figure 4. An example of a thermocline within a deep ocean.
Source: [23].

1. Temperature Related Medical Challenges

At depths within or beneath the thermocline, temperature poses the greatest threat to divers safety. Hypothermia ranks among the most common killers when humans are subjected to cold temperatures for prolonged periods of time. Hyperthermia is "a physical condition that occurs when the body's core temperature falls below 95 F (35 C)"[6]. Hypothermia is fairly rare when subjected to low air temperatures alone, but water amplifies the problem. Compared to air, water has far greater thermal conductivity and specific heat. As a result, the human body loses heat to the ambient water environment approximately ten times faster than in air at the same temperature difference. Thus hypothermia onset occurs much more rapidly in submerged humans [6]. As sea temperatures decline, the onset of hyperthermia quickens its pace.



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 5. Effects on stay time due to cold water temperatures. Source: [6].

An unprotected, lean, human in 60–70 degree F water can be rendered unconscious in as few as two hours. For scale, most NCAA collegiate swimming pools are around 76 degrees F. As such, the need for protection from these harmful temperatures is evident. Many routine diving operations, e.g., ship repair, are conducted in cold waters over many hours, which is only possible through various means of thermal protection for the divers.

2. Thermal Insulation Measures

The U.S. Navy employs both passive and active prevention measures to keep divers warm and on station. Passive measures act as thermal insulation to be worn by the diver, which slows the loss of body heat and the decline of core temperature. The greater the amount of passive protection added, the slower the decline in body temperature. The most common form of passive thermal protection is the wetsuit. Most wetsuits are comprised of a neoprene barrier often encased between two thin layers of cloth. Neoprene acts as a good thermal insulator due to the nature of its composition. Neoprene is a rubber material that has numerous small air pockets within it. These air pockets create a boundary between the ambient water and human skin. Additionally, wetsuits (as their name suggests) trap a small layer of water between the human and the suit itself. This water layer is heated by the human body and insulated by the suit, providing another layer of thermal protection.

Despite their benefits, wetsuits fail to eliminate the effect of the high thermal conductivity of water. In an effort to mitigate this, the U.S. Navy employs the dry suit in temperatures below 60 degrees F [7]. A dry suit is composed of a waterproof rubber exterior, and often contains cotton or wool internal insulation beneath the water proof layer. This suit eliminates any contact between skin and water (save for the hands and face). As a result, these suits slow the loss of core body temperatures more effectively than even the thickest wetsuits. However, given their more rigid construction, they impede motion underwater, and are considerably more expensive than a wetsuit. In an effort to improve the thermal insulation of dry suits, Argon gas can be used to “inflate” the suit around the diver. Argon gas has a thermal conductivity roughly 32% lower than that of air and would slow the transfer of heat from the diver to the surrounding ocean [21]. However, an inflated suit poses significant mobility concerns, and a single tear in the suit compromises the diver very quickly. Naval diving work often involves sharp tools and physical labor, and thus this method is simply too hazardous to the diver to be safely employed. As a result, thick (8mm or greater) neoprene wetsuits are routinely used instead.

While both wetsuits and dry suits offer some degree of thermal protection, a study conducted by the Naval Sea Systems Command concluded that neither suit can offer prolonged protection against very cold water temperatures [16]. As such, several active protection systems have been tested and employed to further combat core temperature loss. One such method is called a “hot water suit.” Normally made from thick layers of neoprene, these suits use umbilical connections with a surface vessel to pump warm water into the suit in order to maintain the diver’s core body temperature. While these suits are very effective at combatting temperature loss, they constrict diver maneuverability, and are solely dependent on a reliable connection to a surface vessel, and may be impractical to implement due to mission specifics. Additionally, should the connection be severed in very cold waters, the diver would be forced to make a rapid ascent, posing severe decompression hazards.

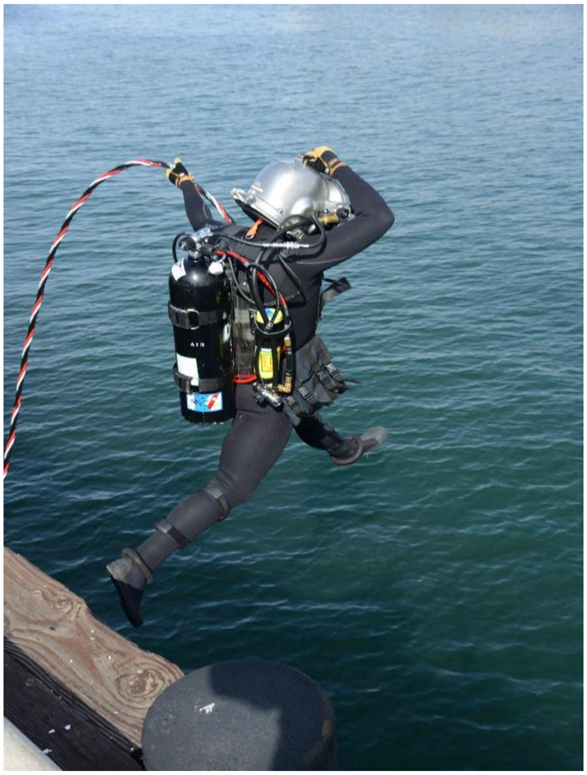


Figure 6. Diver enters the water with a hot water suit connected to surface vessel. Source: [15].

Other methods have been fielded in an attempt to solve the temperature dilemma. In some suits, undergarments with thin electrical wiring woven into it is used to pass a small current which heats the wiring and thus the undergarment, theoretically providing warmth to the diver [16]. However, these undergarments rely on large batteries for their power, which can be bulky and limit mobility. There are also concerns of the wiring or batteries accidentally becoming exposed to sea water and posing shock hazards to the diver trapped within the garment. Finally, these suits are often very expensive and heat the sea water surrounding the diver more than the diver’s actual body. This is due to the simple fact that the surface area on the outside of the suit is greater than within it. As such, more heat escapes into the sea water than reaches the human within the suit. Finally, as with any active system, the electric heating mechanism can fail at depth, forcing the diver to undergo a rapid ascent and risk serious injury from decompression sickness.

While active measures can provide additional warmth to the diver, their downsides (cost, lack of mobility, hazardous) are greater than their benefits. As such, it is clear that a superior passively insulating suit would be the best solution to the thermal dilemma. Currently, the U.S. Navy diving manual indicates when a diver is required to use a wetsuit, dry suit, or hot water suit, depending on the depth and temperature of the water [7]. However, the problems with all three measures of protection remain inhibitive to the divers and pose inherent risks.

3. The Downside of Neoprene

Neoprene is a synthetic material designed to insulate the human body from cold external environments. It is “composed of polymerized chloroprene,” often referred to as “polychloroprene” [32]. This material is fairly resilient to both hot and cold temperatures. In fact, neoprene will safely maintain its structure between -50 degrees F and 275 degrees F [32]. In neoprene wetsuits, the rubber material is structured in a way that creates small air pockets (sometimes filled with nitrogen or noble gasses) called “cells.” These cells are what insulates the human body. However, because the rubber is highly pliable, and the air pockets are easily compressible (a trait that assists with mobility), the insulation is severely reduced at higher pressures. When a neoprene suit is subjected to the higher ambient pressures as divers descend, the insulating air pockets shrink, and the overall thickness of the insulating layer decreases. As such, the rate of heat transfer from the warm diver to the cold ocean increases. As the diver’s body begins to cool, the body will redirect the blood circulation (and consequently, heat) from the extremities to the core to maintain core temperature and prevent the vital organs from shutting down. This leads to significantly reduced dexterity and mobility for the diver; a condition that can be fatal for certain diving operations. As the diver’s temperature falls further, the core temperature will also decline, placing the diver at risk for serious issues such as hypothermia.

4. The Potential Solution

The primary culprit for the reduction in neoprene performance is pressure. In order to maintain a thick, effective, insulating barrier, we aimed to design a material similar to neoprene but one which will not compress under high pressures. Neoprene cells compress because the rubber which composes the exterior of the cell is soft and flexible. Using a rigid material for the cells will allow the trapped air to insulate the body, and will resist changes in volume as pressure increases. Although not necessarily the first material to come to mind, glass microspheres are a potential solution to this problem. The inflexible glass spheres trap air as well as the softer neoprene cells, but are not compromised by higher pressures, as is the case with standard neoprene [18]. This design is hardly a novel proposition. In fact, the Navy Clothing and Textile Research Unit explored the idea of glass microspheres in wetsuits for this exact purpose in 1973. Their tests proved a useful application of the material even to depths of 1000 FSW. Tests "showed that [the] material was essentially incompressible at depths of 1000 FSW" (less than 3% reduction in cell volume) [24]. However, despite the successful tests, the Navy abandoned the idea due to manufacturing limitations. Producing microspheres of consistent high quality was very difficult at the time. Mixing the microspheres with the polymer (in order to create a neoprene-like material) often resulted in the breakage of a high percentage of the spheres. Once broken, the spheres no longer trap air, and thus offer no thermal protection. Today, the combination of modern manufacturing equipment and stronger glass microspheres has allowed for the successful production of a neoprene-like material with minimal sphere breakage. High quality microspheres are now easily produced in industrial quantities and are considerably less expensive. For this project, we outsourced all microsphere production to 3M. Their product, "K1 Glass Bubbles," are ceramic microsphere that can withstand pressures up to 250 PSI, taking divers to more than 500 feet beneath the surface [17]. This breakthrough has revitalized the possibility of solving the neoprene problem.

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II. MATERIALS AND METHODS

A. EQUIPMENT AND CONSUMABLES

In an effort to produce a wetsuit that is as ergonomic as possible, we decided to customize the suit for a specific individual: LT Shane Martin. The customized suit would provide a superior fit and would best demonstrate the capabilities of the new suit. In future iterations of the suit, we expect a less customized approach to fabrication, in order to reduce cost and time. However, as a proof of concept, the fully customized suit best fits the bill. Custom wetsuits are currently produced at dive shops across the country. The standard process involves taking numerous measurements of the swimmer or diver's entire body, then fabricating a neoprene suit to fit the measured dimensions. This is achieved by cutting and stitching neoprene into segments which fit the individual, then connecting those segments to complete the suit. While this process can produce decently customized and well-fitting suits, they still have the limitations stemming from neoprene being used as the thermal insulation material. In contrast, our aim was to produce a superior fitting and thermally protective suit through the use of 3D scanning and a composite material composed of incompressible microspheres. A 3D scan provides a level of detail not attainable through traditional measuring methods. This allows for a near-perfectly fitting suit that will minimize gaps between the diver's body and the wetsuit, improving ergo-dynamics and thermal protection. Additionally, the composite material has been proven to be roughly three times more effective at thermal insulation than neoprene at the same depth [22]. The combination of a 3D scanned fit, and a superior, depth-independent composite material (vice neoprene) allowed us to produce a wholly more effective passively insulating diver suit.

B. PROCEDURES

1. 3D Body Scan Process

Sometimes simple technology can be the most effective at seemingly complicated tasks. This was the case with regard to the job of 3D scanning our bodies (LT Martin and myself). The imaging tool of choice was an Occipital Structure Sensor Mark I. This imaging device is composed of a high-definition camera and an onboard depth processor, optimizing it for 3D imaging. Raw imaging data was converted into usable files in Skanect 3D Scanning software. This software processes raw image data from the Occipital camera and creates a mesh file (.mesh). Mesh files are the standard high definition 3D image file choice.

2. MeshLab 3D Image Processing

Once the mesh file of our bodies was saved, we had everything necessary to design a suit which will be perfectly form fitting suit. However, due to ergonomics and other fabric stitching concerns, the suit was designed to be segmented. As such, it was necessary to modify the full body scan into numerous, smaller, segmented pieces. We decided to make the segments align with human muscular patterns as much as possible. For example, we created a left pectoral piece separate from the right pectoral piece; both of which are separate from the abdomen piece. These three pieces comprise the entire front torso of the suit, but were separated in a manner which allowed for maximum mobility. The body tends to flex and fold naturally along the lines between large muscle groups. This ergonomic consideration was the primary motivation into the pattern of segmentation created. To divide the 3D scan into segments, we used MeshLab, an “open source system for processing and editing 3D triangular meshes” [28]. The initial 3D scan was comprised of roughly 40,000 triangular meshes for LT Martin’s body. Using MeshLab, we were able to perform cuts, and remove portions of the original scan. After cutting away all but the desired mesh (for example: just a left pectoral), the image was saved.

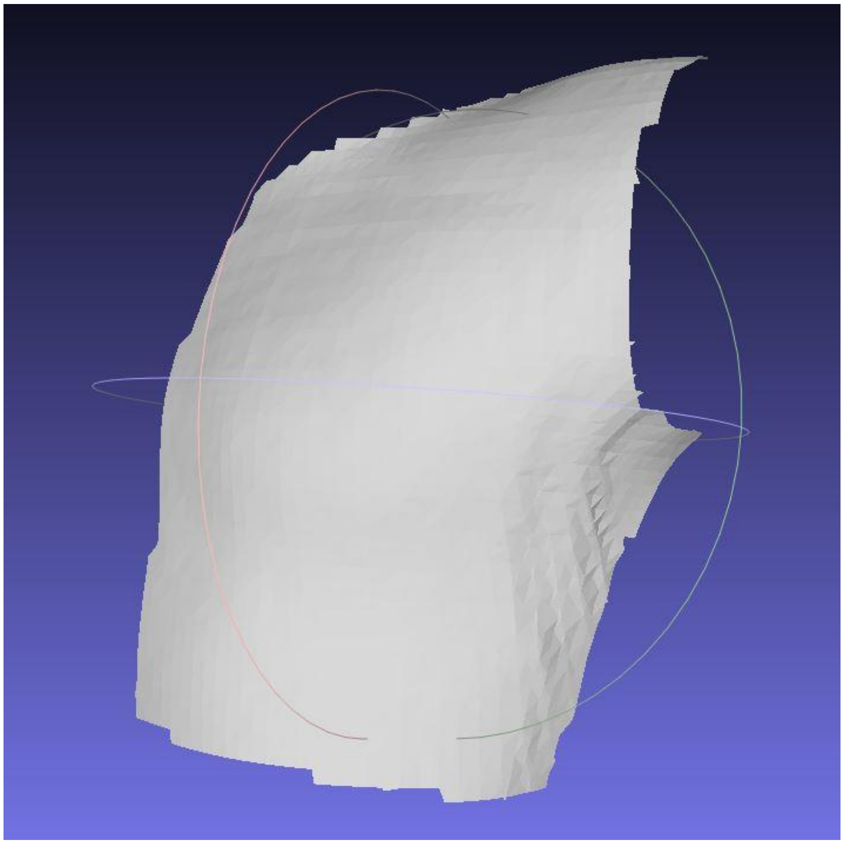

Figure 7. MeshLab image of LT Martin’s left pectoral piece after cuts performed.

Before the new mesh file can be used to create a mold, it must be “cleaned.” “Cleaning” is a process in which the mesh is either simplified, smoothed, or otherwise made to be more easily read and processed by a computer. Meshes with rough surfaces, sharp edges, or extremely high numbers of “faces” (surfaces formed by the three points of the triangular mesh), pose computing risks and may not be modeled properly. When some computer programs attempt to reconstruct meshes with the aforementioned issues, they can often contain build errors, or take extremely long periods of time to construct or modify. In order to prevent this, I performed a cleaning process within MeshLab. This process, called “Simplification: Quadratic Edge Collapse Decimation,” is a function within MeshLab which simplifies an imported mesh file suing the Quadratic Edge Collapse method. This method, while slower than other simplification methods, is able to reduce the number of total faces while preserving the boundary. For the left pectoral piece, we reduced the number of faces from 2667 to 500, effectively smoothing the piece without compromising its outer shape. It is important to note that this process in no way compromises the fit nor ergonomics of the resulting piece for the intended wearer.

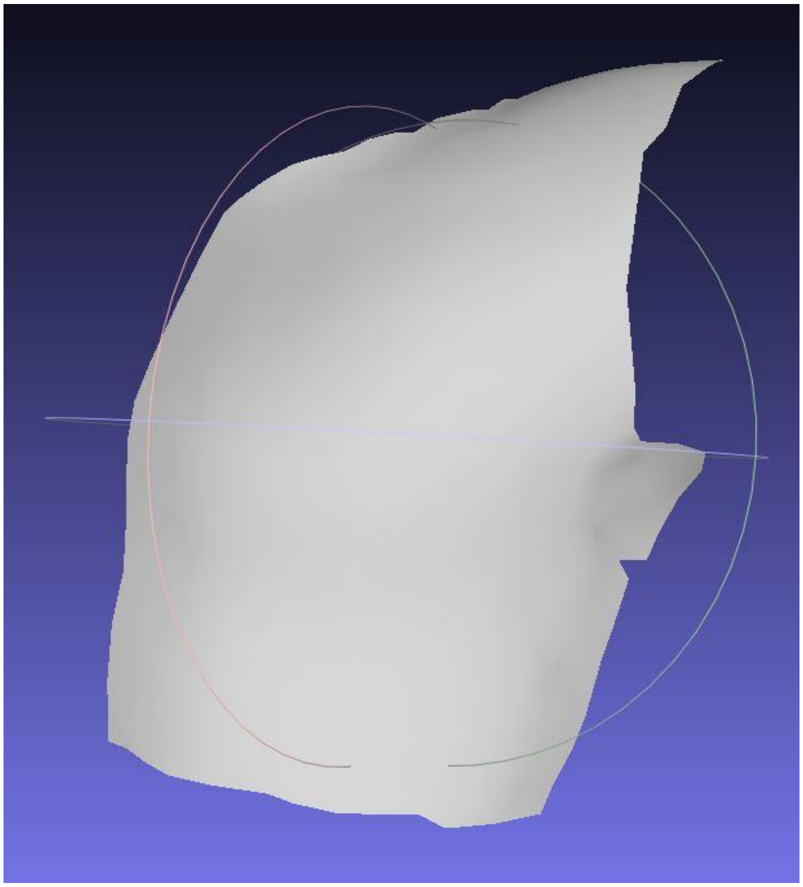

Figure 8. Left pectoral piece after simplification process.

The remaining sharp edges can be cut and removed in a later process, without posing a risk to exportation or reconstruction of the mesh. We exported the new, “cleaned” mesh file using MeshLab and saved it as an STL file. STL files earn their name from “Stereo-Lithography,” and are most common file type for 3D image processing software such as AutoCAD or SolidWorks [13].

3. Solidworks 3D Image Processing

While MeshLab is optimal for importing and simplifying 3D image files, we required a more versatile software to design a 3D mold structure for the individual pieces that were cut in MeshLab. Solidworks is a computer-aided design (CAD) software whose purpose is to model, modify, and create solid three-dimensional products [26]. Although able to import and process multiple file types, we used Solidworks to import the meshes, which we modified and exported via MeshLab as STL files.

Our goal was to create a 3D structure based upon the imported mesh that will ultimately be 3D-printed as a mold, which we could then use to cast our composite pieces. This structure was built around the imported mesh image in order to ensure it was appropriately sized and shaped. While each piece was created separately based upon the size, curvature, and location on the body; there was a general procedure followed within Solidworks.

First, we imported the mesh from MeshLab into Solidworks. Upon successful importation, our object appeared highly similar to how it appeared previously in MeshLab. We performed an initial trim of the object to remove any sharp edges or points which may remain after the MeshLab cleaning process was completed.

Figure 9. Abdomen piece upon importation to Solidworks.

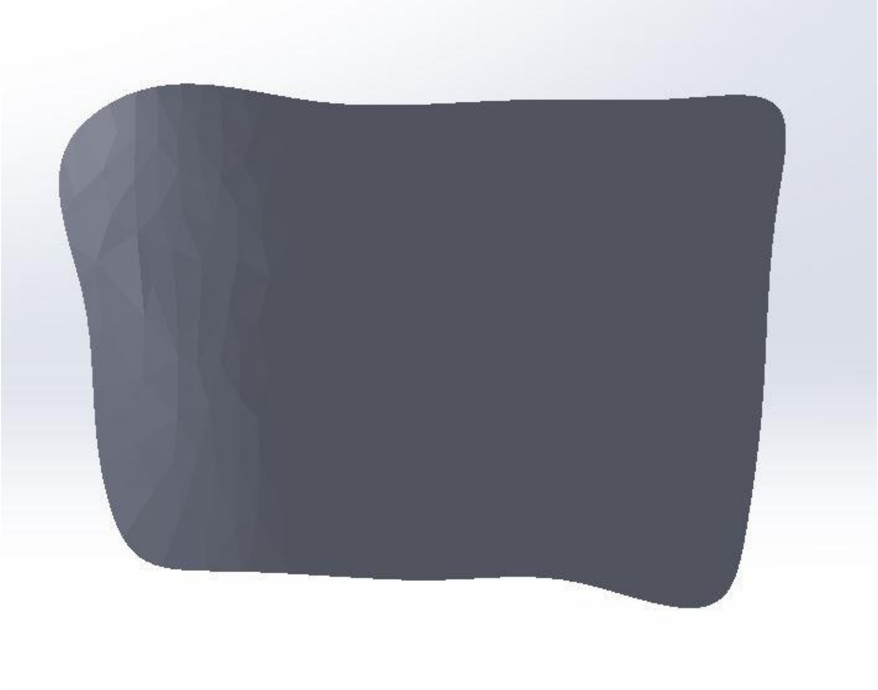

Figure 10. Abdomen piece after trim performed.

At this stage we had removed all sharp edges or other features of the object which were unwanted (for ergonomic reasons) or posed threats to proper modeling and printing of the mold. Next, we duplicated the object and offset it from the original object. The distance of the offset was important as it dictated the thickness of the final piece after casting. This distance will create an appropriately sized void which will be filled with our composite material before solidifying into the final product. To produce a piece that is similar in thickness to common neoprene wetsuits, we offset it by 8mm.

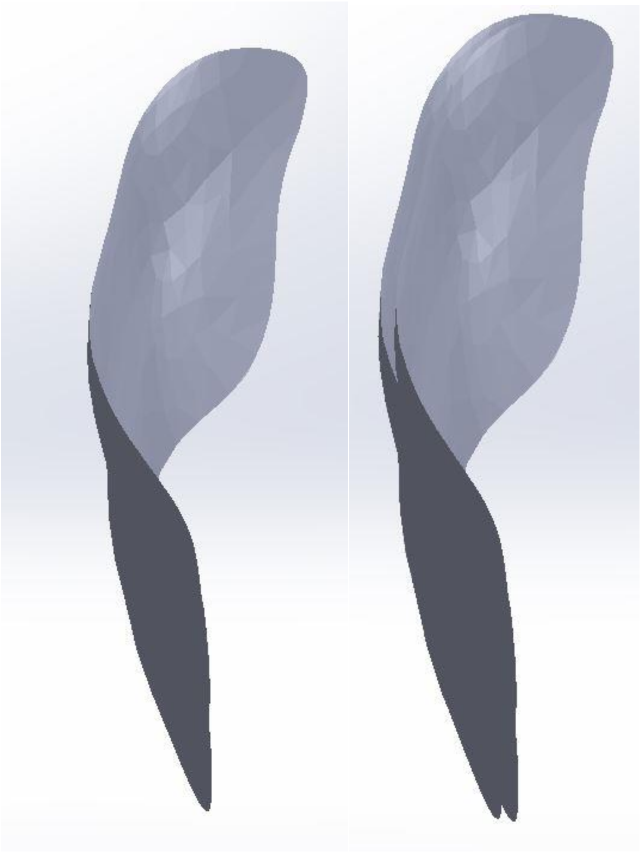

Figure 11. Abdomen piece rotated (left) and duplicated at 8mm offset (right).

Once our piece was appropriately duplicated and offset, we proceeded by beginning to construct the mold around the 8mm gap we created. We did this by performing a task in Solidworks known as “extrusion.” This task uses a known boundary to create an extruded surface out from it in one or two directions normal to the boundary. For this piece, the boundary of the trimmed piece (from previous step) served as the guide for the extrusion process. We capped the end of extruded surfaces by selecting this feature within the Solidworks "extruded surface" menu of options. Upon completion of this step, we had both a top and bottom portion of what will eventually become our mold for this abdomen piece.

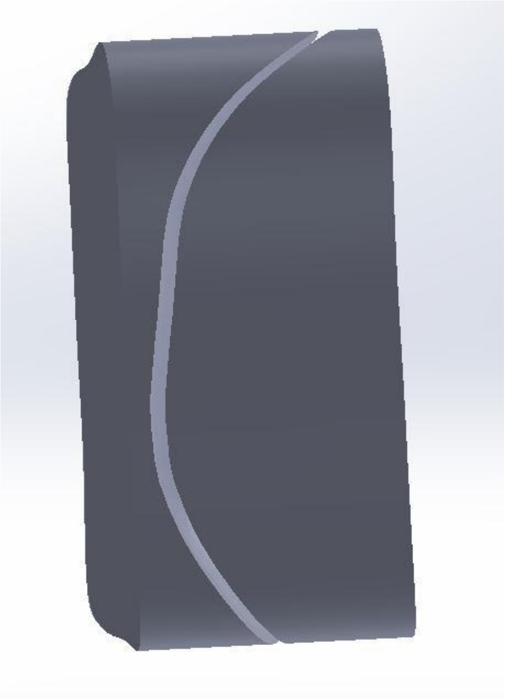

Figure 12. Abdomen piece after extrusion process.

The 8mm gap clearly remains in the above image, while the object is also beginning to take on the shape of a mold. We then created a solid exterior to encase the current object. This casing is necessary because there is no way (with the above object) to contain the material we will pour into the mold, nor is there any way to maintain the 8mm spacing. To create a casing around the current object, we defined the parameters of the case. The simplest way to do this in Solidworks is to use the "sketch" feature to draw a rectangle around the current object. Once the rectangle is drawn, we used it to create a solid case around the above object, again, using the "extrude surface" tool.

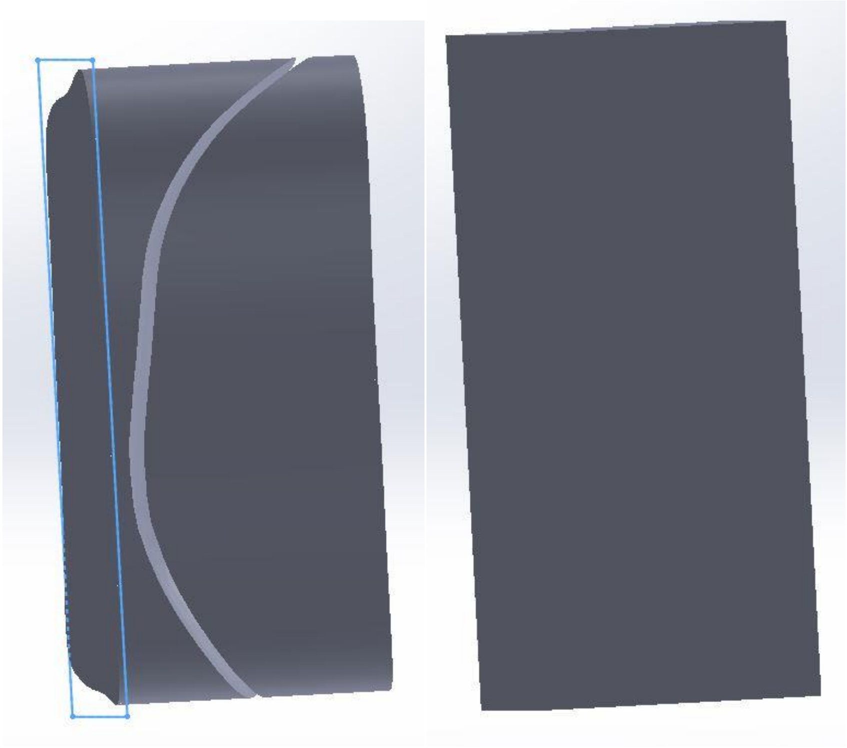

Figure 13. Rectangle is drawn around object (left) and then extruded to create case (right).

It is important to note that there is a 0mm spacing between the case and the object it encloses. That is to say that while we have preserved the 8mm gap between the initial pieces, we had no other gaps within the case. This was done to ensure that the material we will pour into the molds will only create the piece we desired.

We then separated the top and bottom pieces of the mold in order to make finer adjustments to each one individually. Using the “extruded cut” feature within Solidworks, we moved the top piece away from the bottom (temporarily compromising our 8mm gap) while maintaining the appropriate shape of the case.

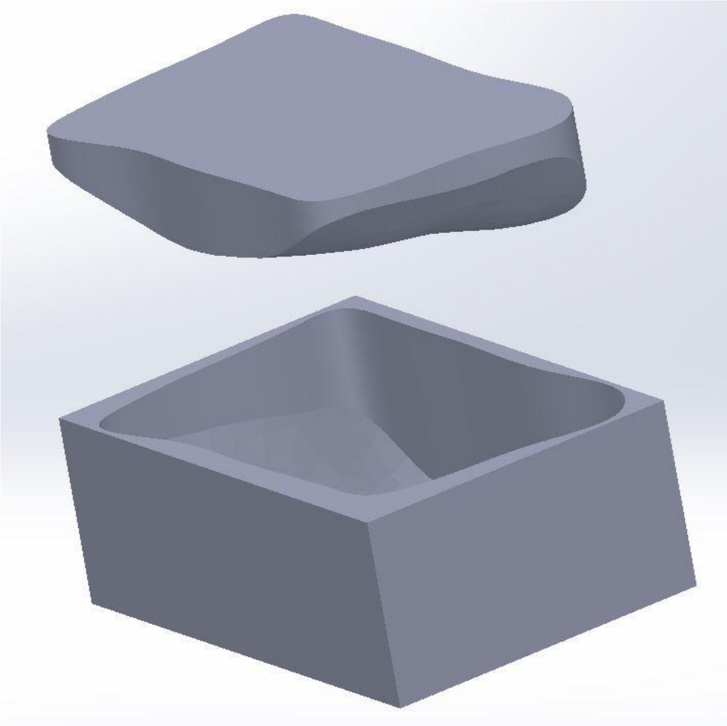

Figure 14. Top and bottom of abdomen mold.

At this stage the object began to take on the appearance of a usable mold. The void within the case (bottom piece) was to be filled with our composite material, then pressed from above with the top piece to create our final abdomen composite piece. Before this could be done, the mold required a way to ensure the 8mm gap was preserved when we pressed the top piece onto the bottom piece. In its current form, we would simply press until there was no gap, eliminating any hope for a successful casting.

We created an additional piece that sat upon the top piece. This piece had the same dimensions (other than depth) as the casing, and therefore fit flush to the casing. We then modified the depth of this additional piece to limit the penetration depth of the top piece into the bottom piece. We sought to re-create our original 8mm gap when rejoining both top and bottom.

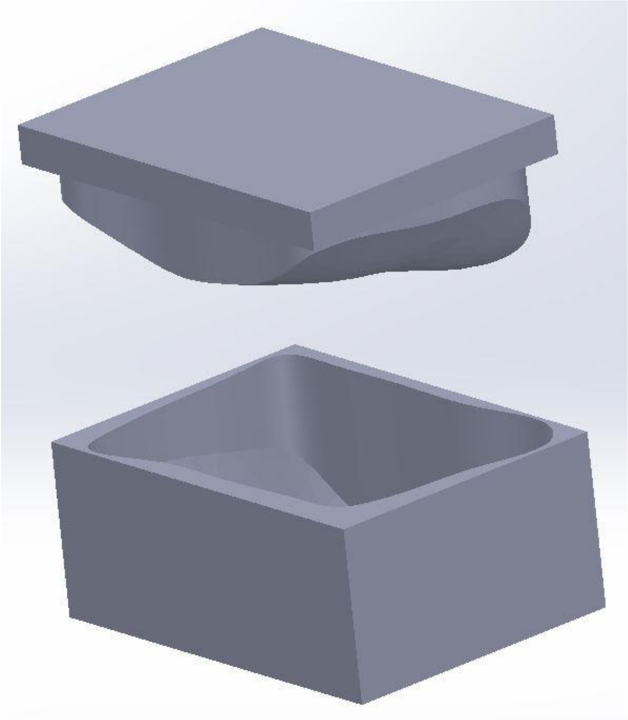

Figure 15. Top of abdomen mold with cap piece.

To be sure there was a gap of exactly 8mm between the top and bottom of the mold, we joined the two pieces, and switched to a “wireframe” view of the mold within Solidworks. This view allows the user to see through the exterior of the mold and take internal measurements. We then used the “measure” tool within Solidworks at different points of our gap to ensure it was 8mm throughout. Once we verified the correct gap depth, we separated the two pieces again, for simplicity.

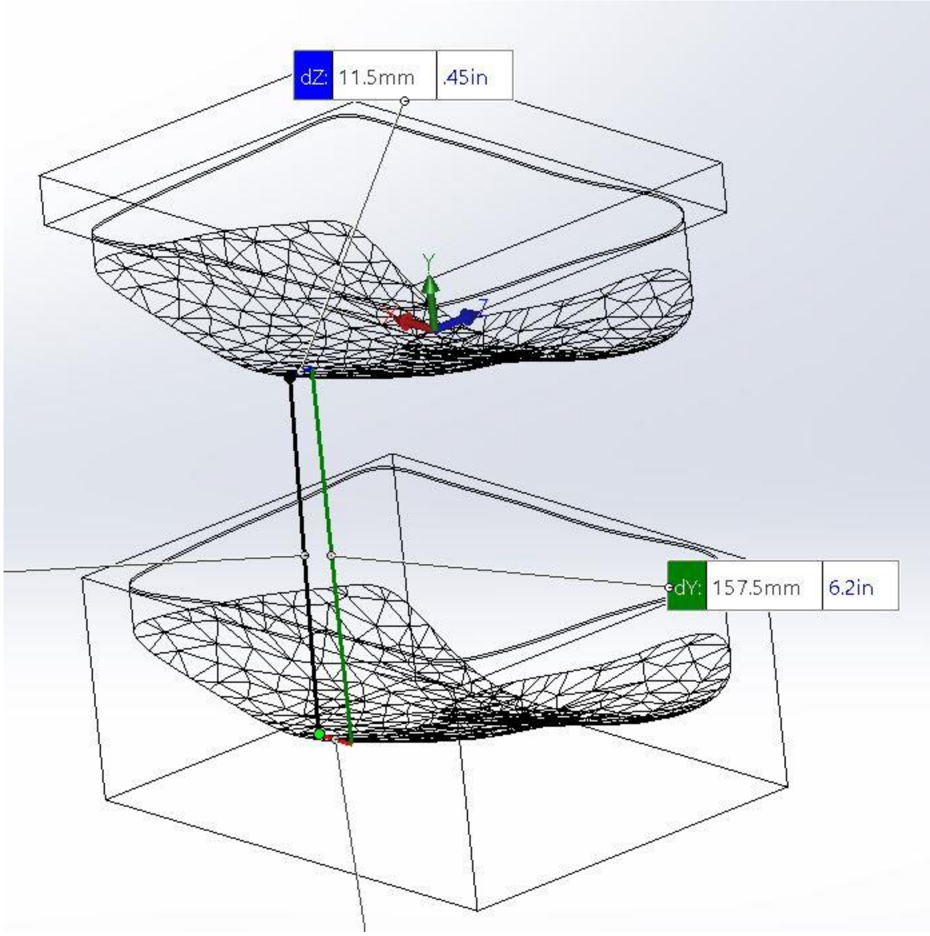

Figure 16. Wireframe view of abdomen piece with example measurements.

Our mold was created in a manner which will guarantee the correct thickness for the final product: our composite piece. The next step was to soften the edges of our case. While this step is not integral to the production of the final piece, it makes the molds safer to handle as there will be no 90-degree angle exterior edges nor sharp corners. The 3D printed molds are decidedly rigid and can be printed at very sharp angles. Softening the edges reduces the risk of injury when handling the molds. We achieved this by using the "fillet" tool in Solidworks. This tool "creates a rounded external face along one or more edges in a solid feature" [26]. We performed this task on all exterior edges of both the top and bottom of the mold.

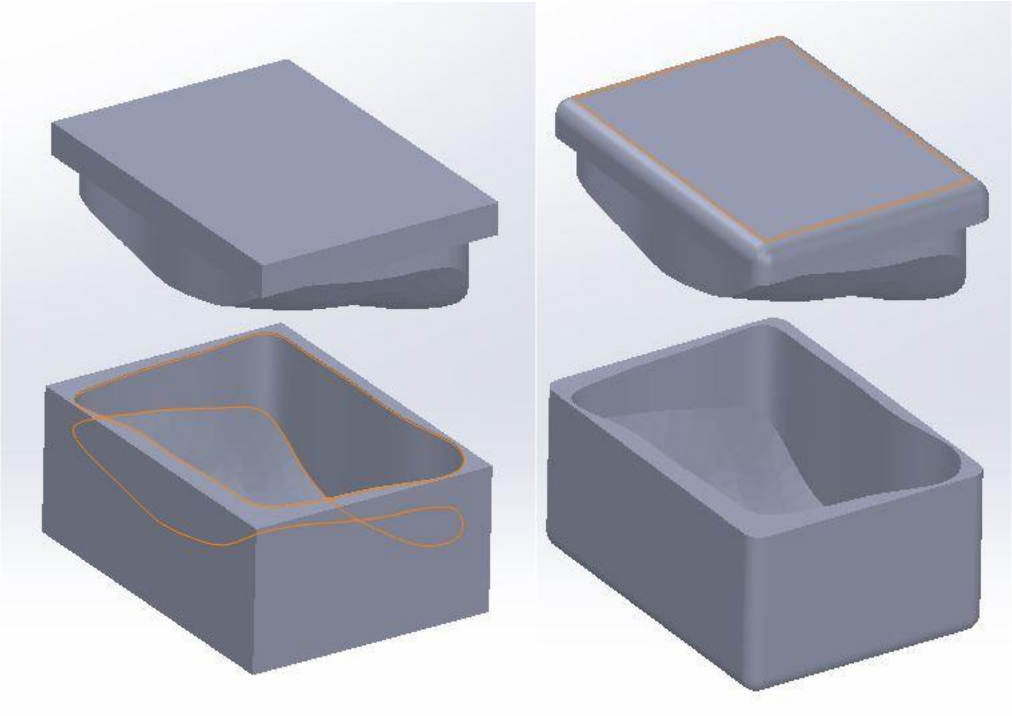

Figure 17. Abdomen mold (left) and filleted abdomen mold (right).

When casting the final piece from the mold, we poured a highly viscous liquid into the mold, which was to solidify into our desired final piece. To accomplish this, our mold required some escape path for liquid composite material not needed to fill the 8mm void. Due to the highly non-uniform shapes of our molds, the exact volume of the void was difficult to calculate. Instead, we estimated the volume and produced more composite liquid than we anticipated needing. When we poured the liquid into the mold, the unused (leftover) needed to be vented out of the mold when the top was compressed into the bottom. To solve this problem, we cut vents into the top piece of the mold. These small holes allowed for unused material to flow up and out of the mold while ensuring the 8mm void was completely filled before any extra material escapes.

To make these holes, we began by using the sketch tool in Solidworks to draw a circle on the top of the top piece of the mold. We created a circle with a diameter of 4mm, which proved most effective at allowing material to flow out without compromising the structural integrity of the mold. We proceeded by copying the circle and pasting it at other locations atop the top piece of the mold. The location and number of circles was determined by the size and shape of the piece which will be cast. We required a sufficient number of circles, in a somewhat uniformly spaced pattern to allow for optimal liquid escape. Once our circles were placed on the top piece appropriately, we used the "extrude cut" tool in Solidworks to cut through the entire top piece. This tool uses the circumference of our sketched circles and extrudes out in both directions from them. Then, it removes all material remaining within the extruded surface: creating our mold vents.

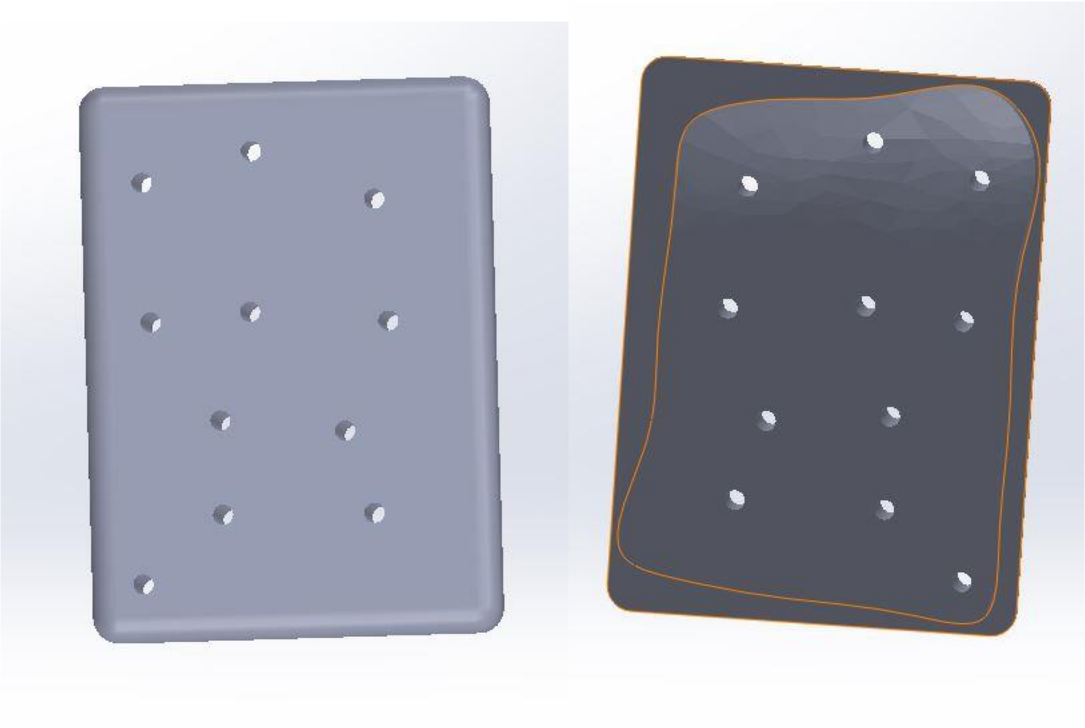

Figure 18. Top of abdomen mold (left) and bottom of abdomen mold (right) with vents cut.

The final step to creating a usable mold was to ensure the top piece would, in fact, fit into the bottom piece. Although their dimensions were exactly the same (aside from depth), there needed to be a small gap between the border of the top piece and the internal border of the bottom piece, otherwise they would not actually slide together.

To create this "wiggle room," we resized the top piece of the mold in Solidworks using the "scale" tool. This tool can shrink or enlarge a given object by a user inputted percentage (of original size). We did not want to scale the 8mm void, but we needed smaller internal borders of the top piece. To achieve this, we performed a 0.98 scaling (98% of original size) of the top piece in the X-direction only. The X-direction is the narrower dimension of the horizontal plane of the top piece. In Figure 14, it can be explained as "left to right" across the top piece. We then performed a 0.97 scaling (97% of original size) of the top piece in the Y-direction only. The Y-direction is the longer dimension of the horizontal plane of the top piece. In Figure 14, it would be "top to bottom" of the image. We did not perform any scaling in the Z-direction, as this would have affected the depth of the top piece and therefore affected the depth of the gap we aimed to maintain at 8mm. Once the scaling was complete, our top piece would smoothly fit within the bottom piece. The gaps between the internal borders of the top and bottom pieces was considerable smaller than the vents' diameters, and thus nearly all extraneous liquid composite material would flow out of the vents, preserving the desired shape of the final product.

We concluded the Solidworks portion of the mold process by rejoining the top and bottom pieces, and saving them as individual STL files.

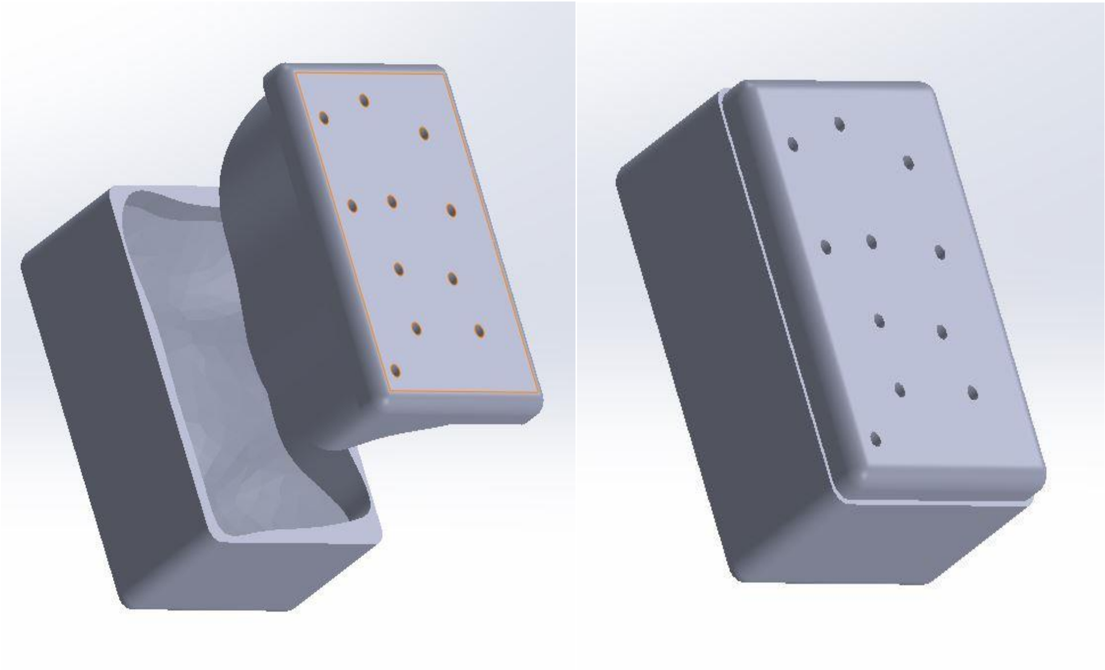

Figure 19. Final mold (left) rejoined (right).

4. 3D Printing Process

While there are numerous ways to manufacture molds for casting purposes, we elected to utilize 3D printing as our method of choice. Key benefits of this choice are accuracy, reliability, speed, and strength of materials. Accuracy is the printer’s ability to print a physical product that closely resembles the digital inputted file. Reliability is a measure of the printer’s ability to do this consistently, from one print to the next. The Naval Postgraduate School is fortunate to have a Fortus 400mc 3D Printer, which we used for the printing of all molds from STL files. The Fortus 400mc is one of the largest and most capable printers available. In terms of accuracy, this printer is capable of resolving digital files down to nearly 127 microns [29], and printing physical parts with this resolution. This resolution far exceeds the needs of our project. Although there is no official measure for reliability, the Fortus 400mc is well regarded as being one of the more consistent printers on the market; a claim we found to be true as it produced duplicate molds with precision.

Figure 20. Fortus 400mc 3D Printer. Source: [30].

Speed is simply a measure of how fast the printer can lay its materials into form, and produce the ordered part. The Fortus 400mc is hardly the fastest printer available today, but it managed to produce each of our molds in less than 24 hours per mold. This convenient speed allowed us to design a mold, print, and utilize the mold for casting all within one week.

Lastly, and perhaps most importantly, is the physical material which the Fortus 400mc uses to print its parts. While this particular printer is capable of printing with over 15 different types of materials, we elected to use polycarbonate. This particular polycarbonate (PC) is developed by Stratasys Corporation specifically for our Fortus printer. This material is capable of withstand temperatures as low as -40 Celsius and as high as 140 Celsius [31]. This ability to withstand heat is necessary as we bake our molds at 80 Celsius. In addition, Stratasys PC ranks among the best materials in terms of tensile strength and flexural strength [31]. This quality allows us to put considerable pressure on the molds (a necessary part of the casting process, to be explained later) without fear of damage or disfigurement.

5. The Casting Process

In order to produce the liquid composite material to be poured into our 3D printed molds, we began with identifying an appropriate pre-polymer and microsphere. The pre-polymer selected was Sylgard 184 polydimethylsiloxane (PDMS). This polymer is naturally low in viscosity. This is imperative because adding microspheres to the polymer raises viscosity considerably. If viscosity is raised too high, the liquid composite will not easily pour into mold or take the appropriate shape for casting. The PDMS came in 1.1 lbs kits from Dow Corning via Ellsworth Adhesives, Irvine, CA. Within each kit is two containers required to create the polymer: Sylgard 184 Silicone Elastomer Base (part A) and Sylgard 184 Silicone Elastomer Curing Agent (part B). Parts A and B are combined in a 10:1 ratio to create the desired polymer.

After selecting the pre-polymer, it was necessary to identify the correct microspheres for our purposes. During the mixing of the pre-polymer and the microspheres, it was plausible that many of the thin glass microspheres may break, greatly degrading their insulating properties. Additionally, we required a microsphere with a high “crush strength” allowing it to withstand the pressures of deep sea dives. We selected the K1 glass microspheres produced by 3M due to their crush strength rating at 250 PSI (equal to a depth of approximately 8250 FSW) and a target fractional survival of 90% [17]. In addition, K1 have the lowest density among the commercially offered microspheres, thereby minimizing the weight of the eventual suit. The combination of the selected pre-polymer and glass microspheres were ultimately compared to the current standard for premium wetsuits with regard to thermal protection: an 8mm Aqua Flex SolAfx wetsuit produced by Aqua Lung.

6. Liquid Composite Fabrication

To begin the fabrication process, we combined parts A and B of the PDMS at a 10:1 ratio. We combined the two parts in 310 mL THINKY mixing jars. These jars are specially designed to fit the ARE-310 rotary mixer, produced by THINKY Inc. of Japan. Before pouring the two parts into the mixing jars, we placed the empty jars on a zeroed VWR E-series 1000 gram balance. We then poured parts A and B into the jar, while using the balance to ensure a precise 10:1 ratio is poured (100g:10g respectively). After pouring the PDMS into the jars, we removed the jars from the balance and placed them into the THINKY rotary mixer. The jars are mixed at 1500 rpm for four minutes. Afterward, the jar was placed back onto the balance and the microspheres are added to the pre-polymer. We added roughly enough microspheres to nearly fill the remaining volume of the jar. We did not entirely fill the volume as we needed some space for mixing to effectively occur. The jar was then placed back into the THINKY mixer and mixed again at 1500 rpm for another four minutes. It was believed that speeds higher than 1500 RPM may result in a higher likelihood of breaking the glass microspheres. In addition, four minutes was selected as it is sufficient time to ensure proper mixing of microspheres into the pre-polymer.

Figure 21. THINKY rotary mixer with jar inserted and times/RPMs set.

After mixing the glass microspheres with the PDMS, the material lost its transparent nature and took on a bright white color. The jars were then placed into a small vacuum chamber, with the lids of the jars removed. We then utilized the vacuum chamber to remove residual gasses from within the liquid material. This step aids in eliminating the chance of air bubbles forming in the material. Air bubbles can expand and, after baking the material, can leave sizable gaps in the material, reducing its effectiveness and possibly making the piece unusable. After performing three cycles of de-gassing in the vacuum chamber, the jars were removed.

The above steps were repeated until enough liquid composite material was ready to be poured into the mold. Each mold, with its unique shape, had a unique volume for liquid composite. As such, the volume was to be calculated to determine how many jars of liquid composite needed to be produced before pouring into the mold. Producing too little liquid composite would result in an incomplete piece after the baking process. Producing too much liquid composite would simply result in some material flowing out of the mold (via the vents). The latter was not a significant problem. Once a sufficient amount of liquid composite was prepared, we poured the liquid into the mold.

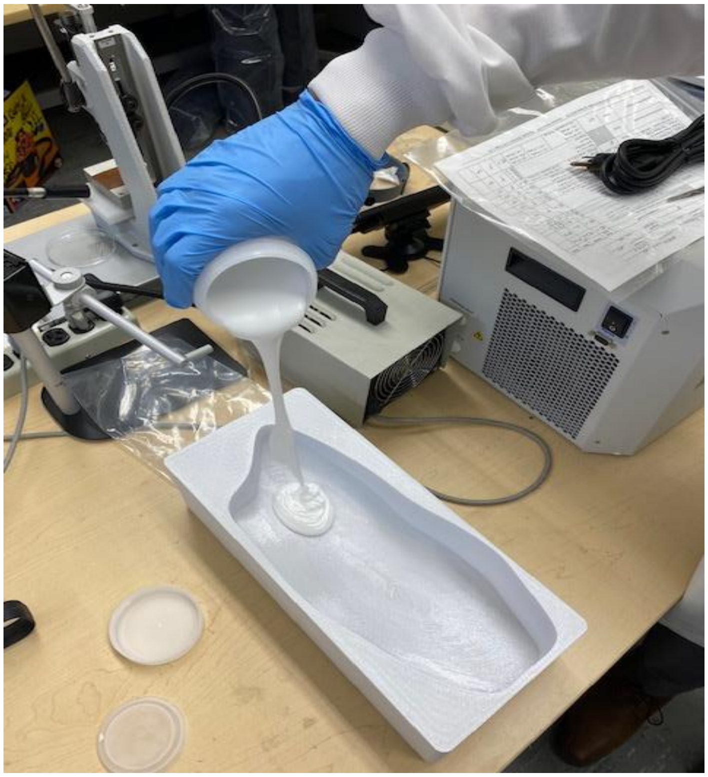

Figure 22. Liquid Composite is poured into the bottom piece of a mold.

The liquid was poured in a manner which avoids “folding” the material onto itself. Doing so can create pockets of air, which we aimed to avoid. After all the material was poured into the mold, the mold lid was placed back on and compressed downward, onto the bottom piece of the mold.

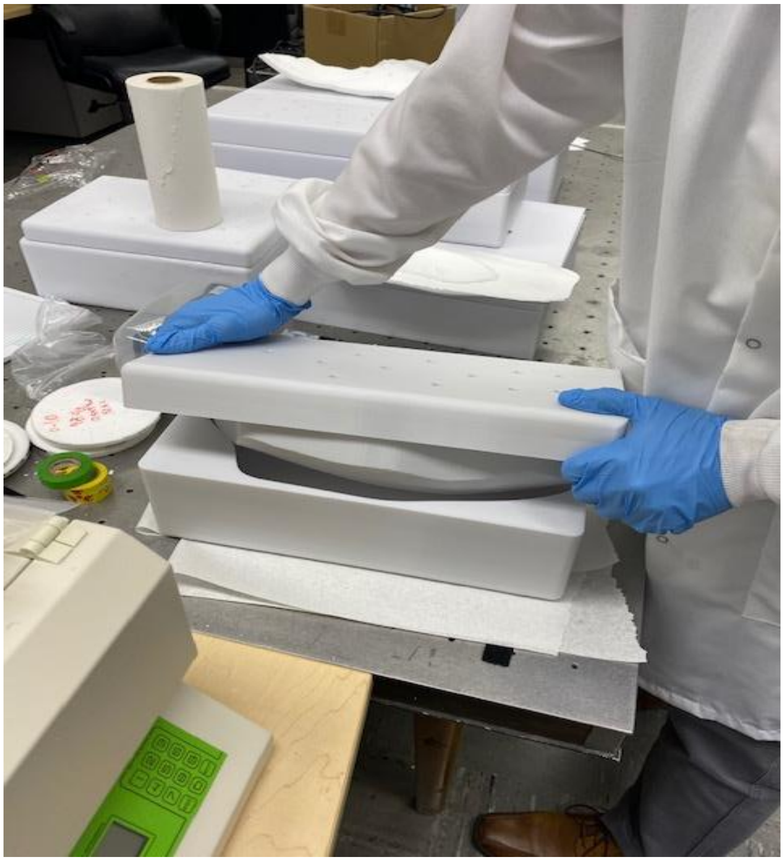

Figure 23. Mold lid is placed on bottom piece and pressed downward.

This compression process ensured that the liquid composite filled the designed void in the mold appropriately. Once the lid was seated properly, and all liquid distributed within the mold, the mold was placed into a VWR Forced Air Oven and baked at 80 degrees Celsius for a minimum of 2 hours.

Figure 24. Mold is placed in VWR Forced Air Oven at 80 degrees Celsius.

While the liquid composite is capable of curing to a solid at room temperature over 24 hours, baking at 80 degrees Celsius shortens the curing time to less than 1 hour and allows pieces to be examined for usability shortly after they are produced.

The final task was to remove the solidified piece from the mold. The composite material tended to stick to the sides of the mold, making it difficult to remove from the mold. Additionally, the liquid material which fills the escape holes of the mold created areas of high surface area where friction between the solidified composite and the holes of the mold made removing the lid of the mold quite difficult. Removing the piece from the mold was accomplished by applying leverage from multiple flat-head screwdrivers, which pried open the lid of the mold.

Figure 25. Composite piece is removed from mold.

Once the lid was removed, the piece could be carefully peeled from the inside of the mold. Finally, the “appendages” which protruded from piece (caused by material in the escape holes) were removed. This was done using a box cutter or other sharp blade.

Figure 26. Final pieces, front and rear, appendages removed.

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III. RESULTS

A. SPECIFIC CALCULATIONS

In order to determine whether our composite material was superior to standard neoprene, several measurements were taken and associated calculations performed. The measurements and calculations examined the thermal, ergonomic, and financial aspects of the composite material.

1. Ratio of Glass Microspheres to Polydimethylsiloxane

During the casting process, it was necessary to mix the 3M K1 glass microspheres with the polydimethylsiloxane. The two parts (A and B) of polydimethylsiloxane must be mixed in a 10:1 ratio respectively as directed by the manufacturer. This is due the nature of the two parts. Part A contains the monomer, while Part B contains the cross-linker and the Pt catalyst. Once this was completed, the amount of glass microspheres to add to the solution needed to be determined. Due to the microscopic size of the microspheres, an approximate determination was practical and sufficient.

Fortuitously, Captain John Brown (a 2019 NPS graduate) experimented with microsphere volumetric percentage (ratio of microspheres to polymer) to identify the optimal percentage in his thesis. His work analyzed the Specific Thermal Resistivity of the material (after mixing polymer and microspheres) at 0 FSW, as a function of varying microsphere volumetric percentages. Percentages varied from 10% to 55% microspheres. At percentages higher than 55%, there is not enough polymer to bind to all the microspheres. When percentages greater than 55% are concocted, the result is partially blended mixture with unmixed microspheres on the surface [22]. This mixture is unusable as its viscosity is too high to be poured, and it is not homogenously mixed.

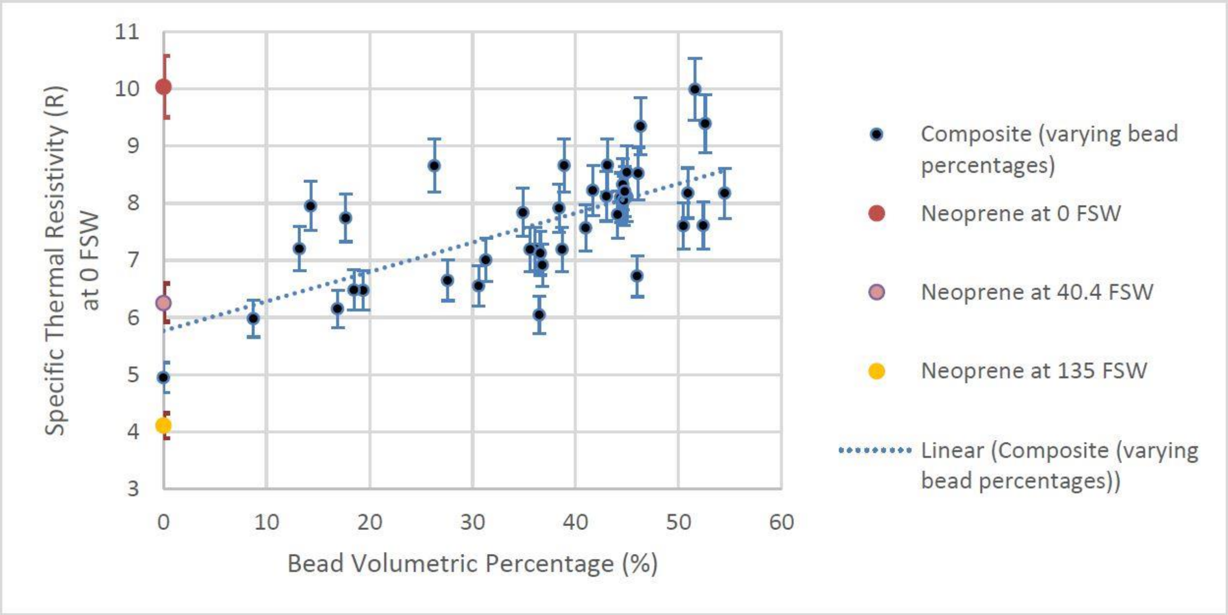

Figure 27. Composite material specific thermal resistivity as a function of microsphere volumetric percentage. Source: [22].

From the test conducted by Capt. Brown, it was determined that approximately 53% is the optimal microsphere content since it still consistently produces pourable and homogeneous mixtures while maximizing microsphere content. This is also close to the theoretical value for a simple cubic lattice. Higher densities are theoretically possible, e.g., by face-centered cubic, but require very orderly arrangement that cannot be achieved in this system at macro-scales and consistently [22].

During the casting process, the polymer was poured into the THINKY mixing jars in the required ratio of parts A to B. The 3M microspheres were then added to the mixture. We added slightly more microspheres than polymer to the jars to ensure we were close to the 53% volumetric content. While this is not a highly precise method, it was reasonably sufficient to ensure we were close to the optimal volumetric percentage while allowing for a timely production of multiple jars of composite. This was important, as some pieces require six or more jars of composite to be cast. In this case, we were also limited by the scale of the equipment available to us. For academic research, the THINKY machine with 310 mL capacity was more than sufficient. In an industrial application, larger mixers would be used, allowing for a single run to mix enough material for the mold, or perhaps multiple molds.

2. Volume of Liquid Composite for a Given Mold

Most pieces require their own individual mold to be cast. The thigh pieces are an exception. We were able to reuse the left thigh mold for the right thigh due to the high symmetry of LT Martin’s thighs and the fact that small adjustments can be made to the cast pieces with a precision knife after they are completely cast.

Due to the fact that many molds were created, it was necessary to determine how much liquid composite must be made for each mold to be appropriately cast. In order to do this, the volume of the mold must be calculated, and an equal amount of liquid must be made to fill that volume. While the exteriors of the molds are rectangular in appearance, the interior void is typically highly asymmetric and unlike common shapes. As such, there was no standard volume equation which can be applied to all the molds. Instead, using a tape measure, we measured the maximum length and width of the interior void of the mold. The depth is the only constant dimension, as we designed it to be precisely 8mm throughout. Using the maximum length, width, and an 8mm depth, we multiplied these values together to calculate a “maximum volume”.

$$\boldsymbol{Max.Vol. = Max.Length * Max.Width * 8mm\ (Depth)}$$

While the “maximum volume” is guaranteed to be greater than the actual volume of the mold’s void, it also guarantees that if we produce enough liquid composite to fill the max. volume, we have enough to successfully cast the piece. This estimation process allowed timely production of pieces without concern of using too little liquid composite and having to recast a piece. The only negative product of this method was that some liquid composite went to waste. Such leftovers would be used more efficiently in a streamlined production process in industry.

3. Thermal Insulation

When the human body is placed in environments where it becomes susceptible to the cold, it prioritizes keeping blood flow (and therefore warmth) to vital organs over “unnecessary” appendages like fingers and toes. This is why often the first part of our bodies to indicates the sensation of being cold are our fingers or toes. Just as our bodies prioritize to keep us alive, so too have we prioritized the construction of the suit to protect the vital portions of the human body. Beginning with the left and right pectoral pieces, we began making pieces to cover the entirety of LT Martin’s torso, front and rear. The torso is home to all of the vital organs save for the brain. Therefore, it was an obvious and important place to begin. After the torso was complete, we made pieces for the left and right thighs. Although home to no organs, the thighs do contain relatively large muscle groups and consequently a sizeable blood volume flows through them. The body circulates heat, oxygen, and nutrients via the bloodstream, and therefore it was imperative to protect the thighs [19]. The next piece we intend to make is a “skull cap” which will cover the top and back of the diver’s head. This is similar to a neoprene diving hood and will insulate the last remaining vital organ: the brain.

The “rule of nines” is typically reserved for determining the extent of burn damage on the human body. However, it stands as a fairly accurate estimation of how much of the body is covered by anything, including burns [8]. The rule of nines separates the body into nine sections and assigns an estimated surface area percentage to each section. In our case, we employ this medical calculation technique to discern how much of LT Martin’s body is protected by the composite pieces (which are currently produced).

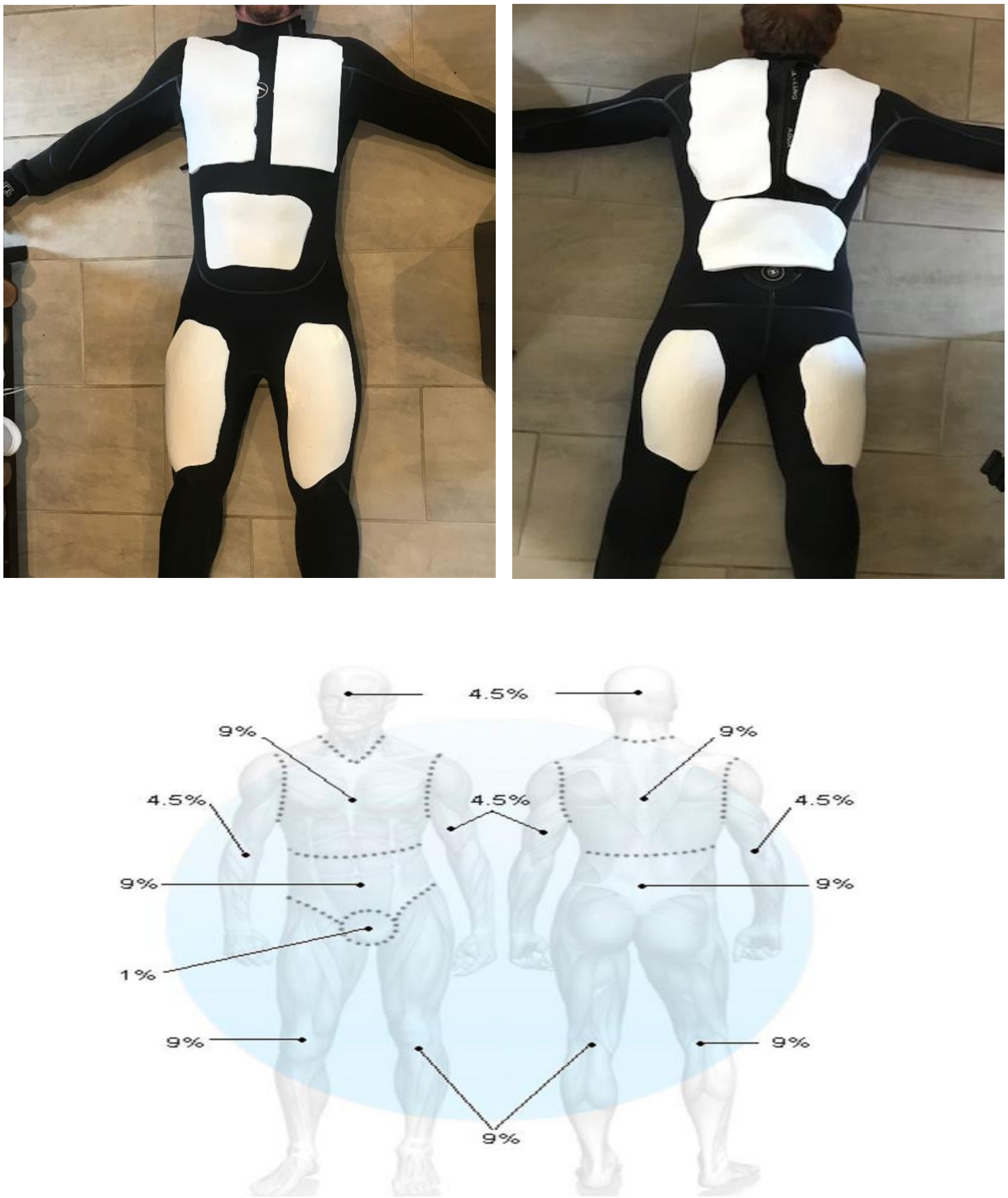

Figure 28. Depiction of composite coverage with reference to rule of nines. Source: [8]

In covering the anterior and posterior torso and the anterior and posterior thighs (shown outlined in red), we have covered roughly 61% of LT Martin’s body. The addition of the skull cap piece will raise that number to close to 70%. Moreover, we have covered nearly 100% of LT Martin’s vital areas.

$$Coverage\ \% = 36\% + (0.7 * 36\%) = 61.2\%$$

This calculation assumes the thighs are 70% of the leg surface area, which in LT Martin’s case, is reasonably accurate.

4. Ergonomics

The *Cambridge English Dictionary* defines ergonomic as “the design of equipment which makes it comfortable and effective for people who use it” [12]. This definition is the basis and highest purpose of our suit. The aforementioned thermal insulance properties meet the “effective” part of this definition, as they allow the diver to safely remain at depths for a longer period of time, to complete their mission. The other and equally important task was to design a suit which is “comfortable” for those who wear it. A comfortable suit allows divers to focus on their work and their safety rather than any suit annoyances or defects. It also creates a plausible solution to the neoprene wetsuit problem, by offering a suit that is at least as comfortable to wear but with better thermal properties. In fact, we expect our segmented suit to be more comfortable than the thick neoprene suits. This is due to the fact that neoprene suits require the diver to fight the spring action of the suit as he/she moves, whereas in ours, the thin nature of the seams would offer much less resistance to the motions of the diver.

The promise but also the challenge with our suit, unlike a purely neoprene suit, is that our suit is segmented. The composite pieces must be designed and arranged in a manner which makes their interaction with the human within the suit “seamless.” Although it may slightly improve thermal insulance, it was not possible to place pieces directly alongside other pieces. This is due to the fact that swimming and diving motions require a large degree of flexibility and range of motion. In order to avoid inhibiting this range of motion, we elected to create small gaps, or “seams,” between pieces. These seams allow for full range of motion to occur without pieces interfering with the motion of other pieces. The locations of these seams was crucial to their effectiveness. We decided to place the seams (and thus the boundaries between pieces) along the lines on the body where two muscle groups meet or border each other.

Figure 29. LT Martin with left pectoral piece.

Figure 29 depicts the considerations for seam placement for the right pectoral piece. We placed a central seam between the right and left pectorals in order to allow for a flexing motion to occur. We also cut grooves near the neck and shoulder, to allow full range of motion for both, while covering as much of the chest as possible. There is a lower seam that is placed above the abdominal muscles and allows the individual to bend forward and flex their abdominals.

These considerations were made individually for each piece, and together they form a network of seams which allow for uninhibited human motion. This was imperative to the overall viability and effectiveness of our suit.

5. Material Costs

The composite pieces are comprised of only two ingredients: Sylgard 184 polydimethylsiloxane and 3M K1 “glass bubbles” (microspheres). Each piece requires differing amounts of each material to be cast, depending on the size of the piece. For a medium sized piece (i.e., pectoral piece) roughly 31 grams of PDMS was required. For larger pieces, such as the lower back and thigh pieces, up to 44 grams of PDMS was needed. Sylgard 184 PDMS can be purchased in 19.9 kg quantities at 2,292.88 USD from

Ellsworth, a large adhesives distribution company [25]. If we consider the largest pieces (44 grams required),

$$PDMS\ Cost = \left(\frac{2{,}292.88USD}{19.9kg}\right) * \left(44g * \left(\frac{1kg}{1000g}\right)\right) = 5.07USD$$

We obtain a total PDMS cost of 5.07 USD to cast a large composite piece. The second component of the composite pieces are the 3M K1 microspheres. Considering the same, large composite piece, we required roughly 44 grams of microspheres to cast. The K1 glass microspheres can be purchased for 19.71 USD per kg from Palmer Holland, a distributor for 3M [9]. Again, for large composite pieces:

$$Microsphere\ Cost = \left(\frac{19.71USD}{1kg}\right) * \left(44g * \left(\frac{1kg}{1000g}\right)\right) = 0.87USD$$

We obtain a total microsphere cost of 0.87 USD to cast the large pieces. Combining the two components' costs, we calculate:

$$Total\ Cost = 5.07USD + 0.87USD = 5.94\ USD$$

Our total cost per piece (for the largest pieces) was roughly 5.94 USD. While this was simply the total cost of material to produce a single piece, if we assume each suit will require about 20 pieces to be produced, our total cost (of materials) for an entire suit is less than 120 USD. This is certainly an upper bound for materials, since economy of scale will drive down the unit price considerably. For comparison, an average quality neoprene wetsuit typically costs around 250 USD or more. This estimate does not include equipment utilization and labor costs, the latter being more difficult to estimate. The primary expense in labor currently is the software conversions, e.g., segmenting, smoothening, cleaning, etc., being done "by hand." However, these are subject to automation through software, which would greatly reduce the required human labor. The secondary labor cost would be the actual casting process, which can also be largely streamlined and automated. Additionally, multiple uses of the same molds further cut the overall cost per suit by a factor equal to the number of suits. Thus, making numerous suits over time, from the same molds, would significantly reduce the total cost per suit and make them considerably more affordable than a high-end 8mm neoprene suit.

IV. DISCUSSION

A. COMPOSITE PIECE PROPERTIES

Further investigation into the thermal properties of the composite material indicates a considerable improvement over standard neoprene. Additionally, the buoyancy of the material, while not specifically measured, must still be considered for future developments of the diver suit.

1. Thermal Properties

The composite wetsuit is worthwhile if the thermal properties of the composite are significantly better than that of standard neoprene. In an earlier study, it was shown that the composite material maintains a near-constant (and greater) thermal insulance value when compared to 8mm neoprene at varying depths.

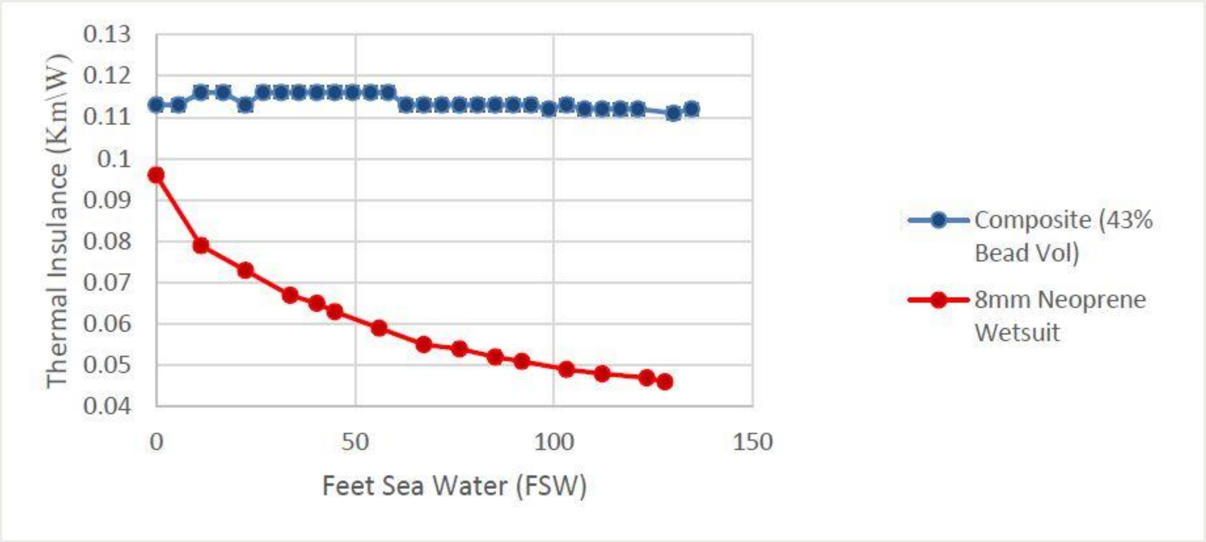

Figure 30. Thermal insulance of neoprene and composite as a function of depth. Source: [22].

The thermal insulance of neoprene quickly declines as depth increases from 0 FSW. By the time we reach a depth of 50 FSW, neoprene may lose nearly 40% of its thermal insulance. Conversely, the composite material sees a negligible (if any) decrease in its thermal insulance at 50 FSW. At 128 FSW, the neoprene has lost over 50% of its thermal insulance. The composite material has seen roughly a 4% decrease at this depth, which will likely go unnoticed to the diver [22].

2. Buoyancy

The air bubbles within neoprene are excellent at maintaining a swimmer's buoyancy at the surface. However, as divers descend, these bubbles compress and suffer a reduction in their buoyant properties. At depth, the buoyant force acts on the air bubbles and tries to push them (and thus the diver) to the surface. As the depth increases, and the air bubbles are compressed, this force is less effective. The compression increases the density of the neoprene air bubbles, thus counteracting the buoyant force being applied by the sea water. This leads to variations in wetsuit buoyancy as the diver descends. In order to control these variations, divers often use buoyancy control devices (BCDs). As the buoyancy properties of their suits change, they must manipulate the BCD to keep them at the depth they desire. Frequent manipulation of a BCD is hazardous as it distracts the diver from their surroundings and the mission.

The composite material, composed of rigid glass microspheres, offers a solution to this problem. As the diver descends, there is no measurable compression of the microspheres. As such, the spheres maintain their buoyant nature, unlike neoprene. Moreover, the buoyant properties of the rigid microspheres are constant with variation in depth. This allows far fewer manipulations of a BCD as a diver changes depths because the buoyancy of their suit is essentially constant. In reducing the need for frequent BCD manipulations we have created a safer, more user-friendly suit.

B. COMPOSITE MATERIAL LIMITATIONS AND PROPOSED SOLUTIONS

Despite the numerous improvements the composite material possesses over standard neoprene, there are limitations of the material that require further analysis and the development of potential solutions.

1. Flexibility

The mobility and range of motion required of swimming and diving demand a suit that is flexible enough to support these requirements. Neoprene, despite its flaws, is suitably flexible and offers skin tight protection with minimal restrictions on mobility. Our composite material is less flexible than neoprene. An 8mm (thickness) sample of the composite material provides considerable resistance to being folded in half. A neoprene sample of the same thickness is easily folded in half. This problem may compromise the range of motion of the diver.

We began to solve this problem with the development of the aforementioned "seams" of neoprene between composite pieces. While this may marginally decrease the gains in thermal protection, initial tests have shown that it greatly improves flexibility by allowing joints and large muscle groups to flex naturally along seams of thin, easily-bent neoprene rather than having to flex the composite pieces. Another potential solution is to identify and utilize a polymer which is more flexible upon mixing with the microspheres. While a more flexible polymer might increase the mobility of the suit, it would have effects on the thermal properties and would need to be independently tested. A final possible solution is to simply make the composite pieces thinner. Neoprene suits range in thickness from 0.5mm to over 15mm depending on the water temperature expected to be encountered by the occupant. The thinner neoprene suits are often used for surface swimming as they are highly flexible but provide less thermal protection than their thicker counterparts. Deep ocean dives often require the thickest neoprene suits or dry suits. In the same manner, our composite pieces could be made at varying thicknesses. A 5mm composite piece was cast and tested and was noticeably more flexible than the 8mm pieces. However, due to the nature of thermal losses, it is expected that a thinner composite piece will not offer the same thermal protection. This has not yet been tested. A future solution may be to provide differing thicknesses for dives to choose from much like they choose their neoprene thicknesses today. We can also vary the thickness of the composite across the suit. Areas that experience very little bending could sustain far thicker composite without significant loss in ergonomics, while areas of greater bending can be covered with purposefully thinner composite, in an engineered tradeoff.

When considering the purpose of the suit, we discerned that the neoprene seams was the timeliest and most effective solution to the flexibility issue.

2. Adhesive Resistance

Initial concepts of the composite diver suit envisioned a neoprene suit with composite pieces adhered to the interior (or exterior) of the suit. However, after testing of 4 different adhesives ranging from neoprene specific binders to simple super glue, nothing seemed to bind with the composite material. This is likely because most of the exposed surface is glass, which is relatively chemically inert. We tried to paint the composite material in order to give it a surface which might bind with an adhesive, but the paint simply dried and peeled off. LT Shane Martin is continuing work on adhesive testing. In the interim, we proposed the idea of sewing thin neoprene “pockets” on an existing neoprene suit. The idea would be to slide our composite pieces into these pockets. The suit with these pockets in currently being constructed and will be tested by LT Martin in addition to his other adhesive tests.

3. Color

The color of the suit has no impact on mobility or performance. As such it is the least concern, but a concern none-the-less. Most neoprene wetsuits are black simply because that is the inherent color of neoprene. Additionally, often a UV resistant additive is added to the suits which is also black. This additive can increase the life of a suit and prevent damage to the neoprene from the sun’s UV rays. While most military divers will be unconcerned by the color of their suit, expanded applications of the suit to Special Forces Operators, who often conduct diving missions, bring about new considerations.

Figure 31. Navy SEALs surface for tactical insertion. Source: [10].

Special forces diving missions often require stealth for covert insertions or extractions. A black suit reflects minimal ambient light and blends in with sea water exceptionally well. Our composite material is white and reflective of light. If the composite pieces were to be exposed to sunlight they would be easily recognizable against a dark sea water background. The first, and most obvious, solution to this problem is to place the composite material on the interior of a dark neoprene suit. This is currently the design for the custom suit (with pockets) that is under construction. A second solution is to possibly mix a dye into the polymer before casting the composite pieces in an attempt to make it black. This has not yet been tested, and might compromise the binding between the microspheres and the polymer.

C. FUTURE RESEARCH

Although we have covered the majority of LT Martin's body with composite material, the diver suit remains incomplete. Future work will include finishing the remaining smaller composite pieces to create a complete composite wetsuit (with neoprene seams). Additionally, other considerations for future work were made that can contribute to an even more effective diver suit.

1. Custom-pocketed Wetsuit

A custom wetsuit made entirely of neoprene is currently being constructed by Otter Bay Wetsuits in Monterey, CA. This suit will have interior pockets for the composite pieces to be placed within. Upon completion of the suit, LT Shane Martin will test the thermal insulation that it offers both with and without the composite pieces added. The test will offer two insights: Does the suit with composite inserts keep the diver warmer (and by how much) and is this suit ergonomically feasible for diving and swimming operations With regard to the first test, using calibrated water proof temperature sensors, LT Martin can measure how much warmer his body remained when wearing the composite suit versus the neoprene-only suit. The second test will involve several dives and swimming strokes to be performed to ensure that there is little or no compromise on human mobility or range of motion while wearing the composite suit.

2. Varying Composite Thicknesses

The initial suit will use 8mm composite pieces throughout. Future iterations can be tested with thicker and thinner composite pieces to measure the changing degrees of thermal protection, as well as to discern if there are changes in mobility with varying piece thickness. This work could identify specific composite piece thicknesses for specific ranges of water temperature, much like the U.S. Navy currently implements for neoprene thicknesses for its divers and operators.

3. Dyeing the Composite

If it is determined that the composite pieces are best utilized on the exterior of a neoprene suit, or perhaps woven into a suit in a manner which exposes their bright white color, testing a dye additive may be worthwhile. As previously discussed, white wetsuits will be easily spotted against dark backgrounds and nearly eliminate the ability for a covert operation to be performed. Future tests could focus on adding a dark, inert, dye to the polymer before mixing with the microspheres. This mixture can then be cast in the same manner and tested. The goal would be to identify a dye which mixes with the current recipe without compromising the beneficial thermal protective nature of the composite.

V. CONCLUSION

In the inherently hazardous profession of diving, anything which improves safety and efficacy of the diver should be considered necessary. Exposure to cold temperatures is more than an annoyance, it poses severe health risks and can become fatal. Aside from possible bodily harm, cold exposure minimizes the time the diver can spend on a task and deviates his/her focus from the mission.

In addressing this problem, we considered the nature of the problem itself: neoprene's poor thermal insulance at depth and the lack of viable alternatives to neoprene suits. Our composite material, in combination with neoprene seams, allows for a superior thermally insulating suit to be manufactured while also maintaining the flexible properties of neoprene necessary to allow for swimming and diving motions to be uninhibited. Previous thermal insulance tests confirmed that the composite material is considerably more thermally insulating when compared to neoprene. Additionally, ergonomics test conducted with LT Martin have verified that the suit is comfortable to wear and poses minimal inhibition to swimming and diving motions.

Future testing will explore the viability of adhering the composite material directly to neoprene or to utilize sewed pockets within a neoprene suit to contain the composite pieces. We expect future iterations of the suit to have variable composite piece thicknesses (for different water temperatures) and a smooth integration of the composite with the neoprene. The clear vision for future iterations of the suit speak to its feasibility and practical utility.

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