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THESIS

**DEPTH INDEPENDENT THERMAL
INSULATION FOR DIVING SUITS**

by

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March 2023

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DEPTH INDEPENDENT THERMAL INSULATION FOR DIVING SUITS

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This research further improves previous designs of depth-independent thermal insulation K-suits. It has already been proven that a K-suit (using a generic shape design that can adapt to most body shapes, constructed by a glass microsphere elastomer mixture) provides greater thermal protection without sacrificing ergonomics, unlike the thicker neoprene suits. This project improves this wetsuit by doubling the amount of insulation, improving the efficiency of the production work phase, and improving construction of the wetsuit design. Typically, wetsuit designs have an inverse relationship between thermal protection and ergonomics of the wetsuit, which severely hinders the working diver over the recreational diver. This project breaks that mold and creates a more ergonomic and better insulated wetsuit that will make the working diver warmer, safer, and more productive.

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I. INTRODUCTION

A. A BRIEF HISTORY OF DIVING

Professional diving dates back nearly 5,000 years. It originates from humankind's need to forage for food and tools to trade. The first salvage jobs were for items like food, sponges, and pearls as seen in Figure 1 [1].



Figure 1. Early attempt of a diving suit with a leather bag over the head, with an air tube to the surface. Source: [1].

One of the first state-sponsored divers was recorded by a historian named Herodotus. He wrote down the story of a diver named Scyllis, who was hired by the Persian King Xerxes to recover treasure from sunken ships [1].

As humans evolved, so did diving. Three different styles of diving evolved: recreational, commercial, and military. Today, the U.S. Navy is the leader in the development of diving procedures and diving tools. This includes life support systems such as the self-contained breathing apparatus (SCUBA) and the protections divers wear while conducting operations as seen in Figure 2.



Figure 2. A diver shows the importance of using a neoprene wetsuit for thermal and physical protection.

B. PHYSICAL AND THERMAL PROTECTION

The suits that divers wear on their bodies provide two separate types of protection. The first being physical protection from wildlife, industrial environmental hazards, or even polluted waters. The SCUBA outfit without a wetsuit or coveralls is the least protective in nature. Deep sea gear with a hard helmet provides the most amount of physical protection.

The second type of protection the suits provide is thermal protection. The unprotected, non-working diver requires a water temperature of approximately 91 degrees

to maintain a stable body temperature [1]. This is due to the higher thermal conductivity of water verse air, nearly 23 times more conductive [2]!

As seen from Figure 3, a core temperature of 97 degrees F, only one degree below normal, will cause a loss in functionality for the diver and therefore decrease the productivity of the diver. Losing diver productivity leads to increased bottom time, or the time the diver is consuming nitrogen because of breathing compressed air. Consumption of nitrogen increases the risk to the diver. Figure 3 explains the symptoms associated with a lowering core temperature from a normal temperature of 98 degrees Fahrenheit to 79 degrees Fahrenheit.

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. Signs and symptoms of lowering core temperature. Source: [1].

The loss of different human functions is scalable based on the amount of protection worn, the exertion output, and water temperature. Figure 4 summarizes these times, however just like any information regarding human physiology, these are statistical and there are always outliers.

Water Temperature °C / °F	Loss of Dexterity without protective clothing	Exhausted or Unconscious (drowning without flotation)	Maximum swimming time for self-rescue	Likely Survival Time (with flotation)	Maximum Survival Time (with flotation and protective gear)
0.3 / 32.5	<2 min	<15 min.	Nil	<15-45 min	1.4 hrs
0.3 to 4.5 / 32.5 - 40	<3 min	15-30 min	0-7 min	2-3 hrs	1.5-5 hrs
4.5 to 10 / 40 - 50	<5 min	30-60 min	7-40 min	2-3 hrs	5-12 hrs
10 to 15.5 / 50 - 60	10-15 min	1-2 h	40-75 min	3-5 hrs	12-22 hrs
15.5 to 21 / 60 - 70	30-40 min	2-7 h	75-105 min	4-17 hrs	22-36 hrs
21 to 26.5 / 70 - 80	2 h	7-12 h	105-140 min	>17 hrs	36-54 hrs
>26.5 / >80	2-12 h	>12 h	>140 min	>17 hrs	>54 hrs

Figure 4. Cooling effects of immersion in cold water. Sources: [3], [4], [5].

The typical defense against cold conditions during cold water diving operations is wearing a neoprene wetsuit or dry suit. The colder the temperature, the thicker the neoprene

wetsuit required to insulate the diver. The wetsuit works by trapping a thin layer of water against the diver's body, which is then warmed to keep the diver insulated from the colder water on the outside of the wetsuit [6]. The inherent problem with wetsuits, is that when the water gets very cold, the wetsuit needed is very thick, in the 6–8-millimeter range and the ergonomics of the suit decreases significantly. Every movement takes a lot of energy to bend and compress the suit, which requires higher oxygen consumption and longer bottom times. This increases the risk to the diver. The neoprene wetsuits have another inherent challenge that divers face during operations. The wetsuit compresses as the diver increases depth, lowering the thermal insulation of the wetsuit and changing the diver's buoyancy as seen in Figure 5 [7]. The two main problems with the neoprene wetsuit are its ergonomics and depth dependence.

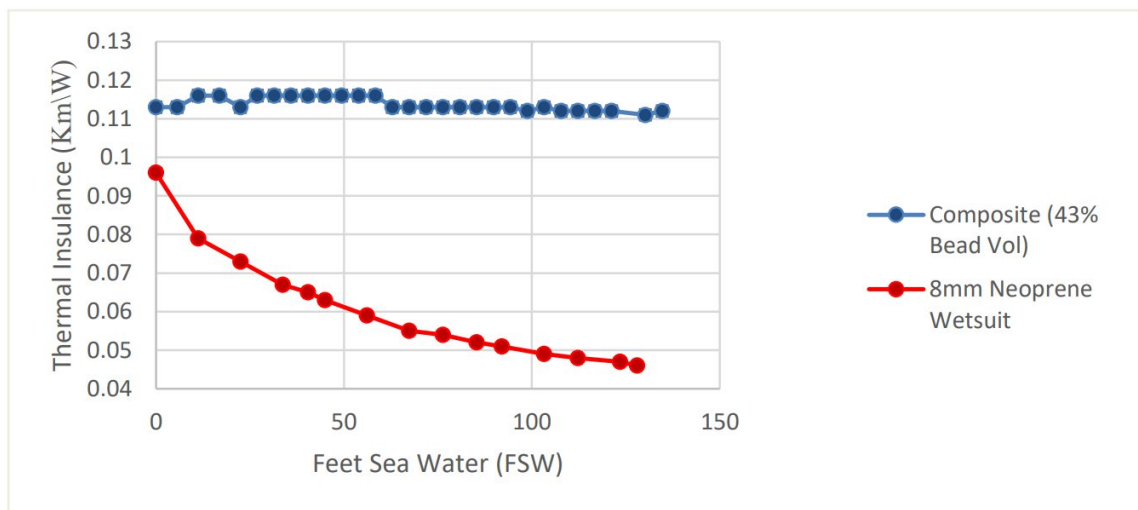


Figure 5. The relationship of depth and thermal insulation of a neoprene wetsuit compared with a composite bead solution. Source: [7].

Another option for thermal protection is the dry suit, which does as its name suggests, keeps the body of the diver dry. The problem with the dry suit is that the air inside the dry suit affects the buoyancy of the diver, and that air compresses and expands as the diver vacillates in depth. This problem has led to a loss of buoyancy control and diving related sicknesses such as decompression sickness. Also, dry suit has the risk of a breach

(e.g., by mechanical damage from the environment, whence the air would escape, with potentially catastrophic loss of thermal protection and buoyancy for the diver).

II. PRIOR WORK

A. HISTORY OF THE DEPTH INDEPENDENT THERMAL INSULATED WETSUIT

Previous Naval Postgraduate Students (NPS) have been working on a solution to this problem for several years now. Students such as Brown [7], Demers [8], Martin [9], and Waldron [10] developed a material from glass microsphere beads mixed with an elastomer glue and curing agent that provides great thermal insulation and does not compress at depth. Much of the background work and testing of the mixture was done by Brown and Demers. Martin poured the mixture into molds that were created from 3D body scans [9]. This worked well for the owner of these body scans but with the many different body shapes that exist, it was less effective for the others. Figure 6 is the completed wetsuit created from Martin's 3D body scans.



Figure 6. Shane Martin's finished wetsuit with molds made from 3D body scans. Source: [9].

Waldron eventually created a mold compatible with most body shapes and curvatures. The chocolate bar mold was created using a simplistic grid system that could

be adjusted to fit the desired size. Then molds of two different radii of curvature (named R5 and R1) were created to accommodate the flat portions of a human body such as the stomach and back and the curved portions like the arms and legs as demonstrated in Figure 7 [10].

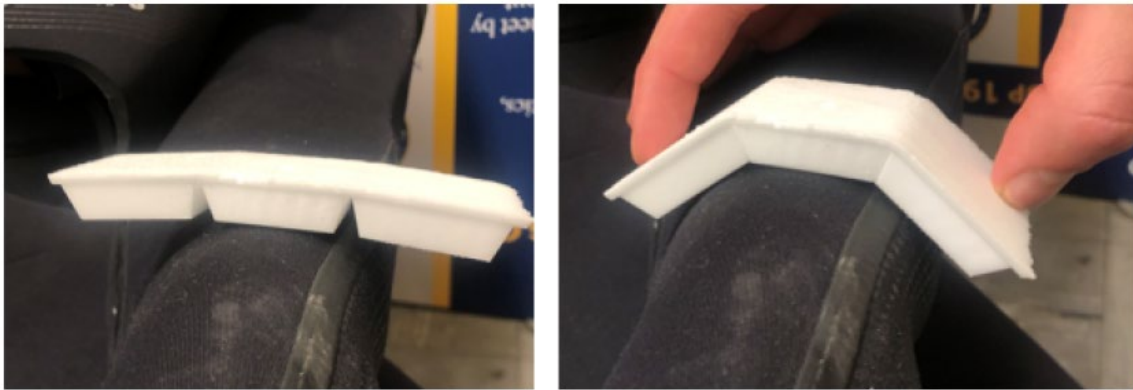


Figure 7. An example of the chocolate bar design tested on a curved portion of the wetsuit. Source: [10].

Sewing these chocolate bar molds into the wetsuit also generated complications with the sharp, 90-degree corners. Overall, Waldron proved it is possible to use these molds to create a better performing wetsuit than a traditional 7 mm wetsuit.

The next step was to improve upon Waldron’s design in three different phases: the manufacturing process, the wetsuit fabrication, and the performance of the wetsuit. The overall goal was to generate a wetsuit with double the number of molds that Waldron’s used to verify increased thermal performance.

B. AREAS TO IMPROVE

Because of the goal of the new wetsuit, there was nearly double the amount of work required to create double the number of molds. Increasing the efficiency of this process would not only further the capabilities of future research but would also improve the futuristic batch method used in the private sector.

The first process to improve was transferring the mixture from the mixing vessel to the degassing container. Each mold requires three or four mixing vessels to fill them, depending on the type of the mold. Each time one mixing vessel was poured into the degassing container, it would take approximately four minutes of holding the container upside down to complete the mold because of the viscosity of the liquid. Estimating that the suit takes approximately 40 molds, at an average of 3.5 mixing vessels per mold, that equates to over 500 minutes of holding vessels upside down to conduct the transfer portion. This doesn't account for transferring the mixture from the degassing container to the mold itself.

The degassing itself required areas of improvement. Although the previous team used a wide container to perform the degassing, allowing for a larger surface-to-air interface while applying suction, it still required nearly two hours of degassing to remove an adequate amount of the air in the mixture. Then once the mixture was poured into the mold itself, the folding action of the viscous mixture introduced more air bubbles that became troublesome after it cured as seen in Figure 8. Not only did the extra air reduce the thermal effectiveness of the suit but it also increased buoyancy issues with the already very buoyant suit.

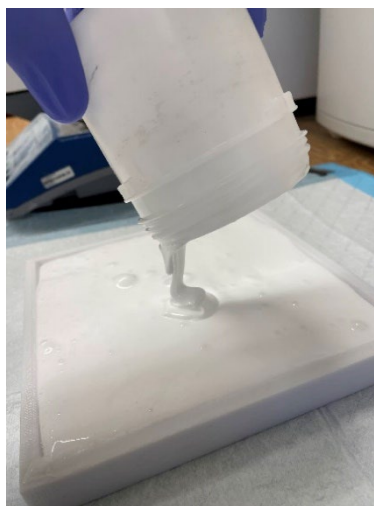


Figure 8. Air being introduced to the mold from the folding action during the pour.

The challenges with placing the square or rectangular molds into the wetsuit were only exacerbated by trying to place two of the same molds in one pocket. Not only did increasing the depth of the insulation add to the pocket shape issues in the wetsuit, but the issue of sealing the pockets to prevent water from entering was already a prevailing problem in previous versions of the wetsuit. The pockets needed to be sealed to prevent cold water from entering and changing the buoyancy of the suit. Also, other divers had problems with the tightness of the suit around the openings of the neck, wrist and ankles.

III. MATERIALS AND METHODS

A. MANUFACTURING PROCESS

The basics of the procedure were the same for the last few projects, using the same ratios and mixing times.

First, a two-part Sylgard 184 Polydimethylsiloxane (PDMS) kit was mixed at a 10:1 mass ratio of elastomer to curing agent in a 300 milliliter (mL) plastic beaker. Hollow 3M K1 HGM, with a mean diameter of 65 microns [27; citation in original], were added at a 3:2 volumetric ratio. The target mass formula was 9.00 g of curing agent, 90.00 g of elastomer, and 10.00 g of HGM. In a planetary centrifuge, given in Figure 3.7, the mixture was spun at 1500 Rotations Per Minute (rpm) for four minutes. Prior to spinning, the centrifuge was balanced by adjusting weights to the final mass. As a precaution, goggles, a disposable mask, and gloves were worn when preparing this mixture to reduce contact with the HGM. When handling the glass powder, the lab door and windows were left open for greater ventilation. [10]



Figure 9. The planetary centrifuge prepped with the correct settings to start mixing.

After completion in the planetary centrifuge, the procedures started to diverge from those employed by the previous students. The mixtures, in their mixing containers, were placed directly in the vacuum chamber for 1.5–2 hours with the vacuum running continuously. The vacuum chamber pulled the gases out of the solution that were originally introduced into the solution while in the centrifuge. The mixtures were then transferred from the mixing containers to the mold after the 1.5–2 hour period using a wooden disposable popsicle stick. This popsicle stick became the best method of transfer because they are low cost and disposable. Attempts to use items like silicone cake spatulas caused the material to bond to the spatula and ruined the spatula after its first use. This minimized the folding action of the viscous liquid and introduced less air while transferring the material. The mixture was left for another one hour waiting period in the mold to allow for more air to escape as demonstrated in Figure 10.

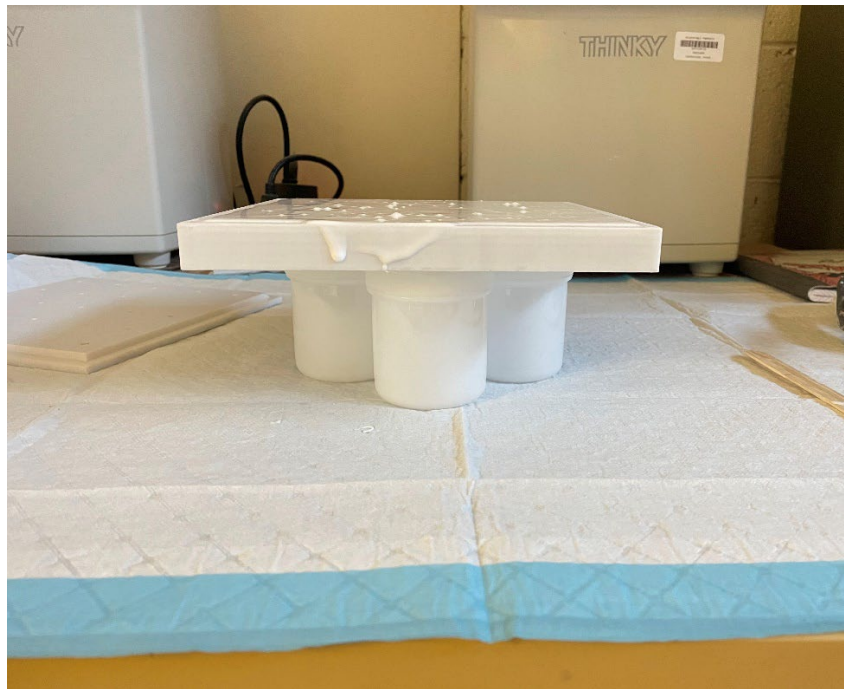


Figure 10. The one-hour wait time allowing more air to escape as seen from the bubbles at the top.

This additional wait period was crucial to obtaining a good result in the light test and minimizing the porosity. Porosity was an important characteristic of the mold because

the more porous the mold, the more air in the mold, which lowers its thermal insulation properties as well as introduces more buoyancy. This qualitative light test was done by holding up the mold to the light to view the amount of air in the mold as seen in Figure 11.

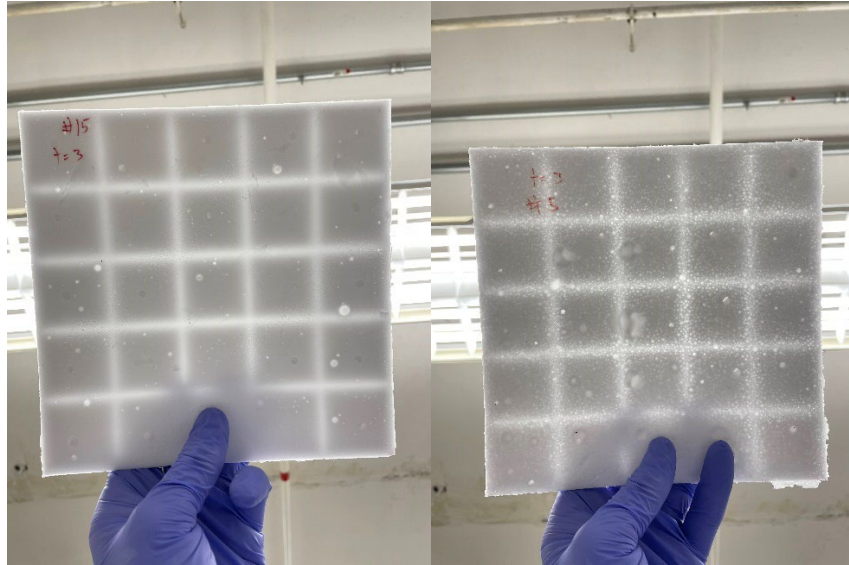


Figure 11. The difference of porosity between a mold with the additional 1 hour wait time in the mold (left) and a mold without (right).

The mold was clamped with a three-millimeter backing in the four corners of the mold with C-clamps. This was accomplished by elevating the mold like in Figure 10, to get the clamps under the mold without spilling the mixture. Clamping in the four corners, as shown in Figure 12, vice towards the center or trying to use a dead weight was also crucial to the uniformity of the mold. When clamping towards the center or using a dead weight, the mold cover bent causing a thinner section in the middle.

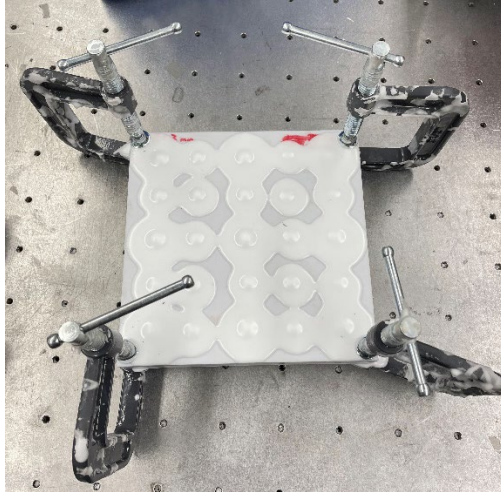


Figure 12. An example of a clamped mold ready for the curing process.

The mold then went into the oven at 80 degrees centigrade for 2 hours. More time in the oven did not damage the mold. However, to prevent extra wear on the oven, the timer was used and was set at 2 hours. During this time, the mixing containers were placed on petri dishes, upside down and at angle, to allow the material to pour out, and were placed in the oven during the same two hours. This allowed for the material to cure on the mixing container, which then allowed for easy peeling of the material off the container, and for the container to be re-used again. The angle, as demonstrated in Figure 13, was a crucial component to the ease of cleaning the mixing containers daily.



Figure 13. The mixing containers cured in the oven, allowing them to be cleaned easily.

After the two-hour baking period, the mold was allowed to cool to the touch. If the mold was still warm while one attempted to remove it, there was a higher chance of it breaking. A chisel set was used to slowly pry open each side of the square lid evenly to prevent the lid or the mold from breaking as seen in Figure 14.



Figure 14. An example of using the chisels to remove the lid slowly.

After the mold was removed, it was repaired during the creation of the next mold by using the next mold's left-over material to fill in whatever defects were present. Most often, a few air bubbles would reach the surface during the curing process. Using a popsicle stick and some left over material, those air bubbles or defects were filled in and corrected as seen in Figure 15.

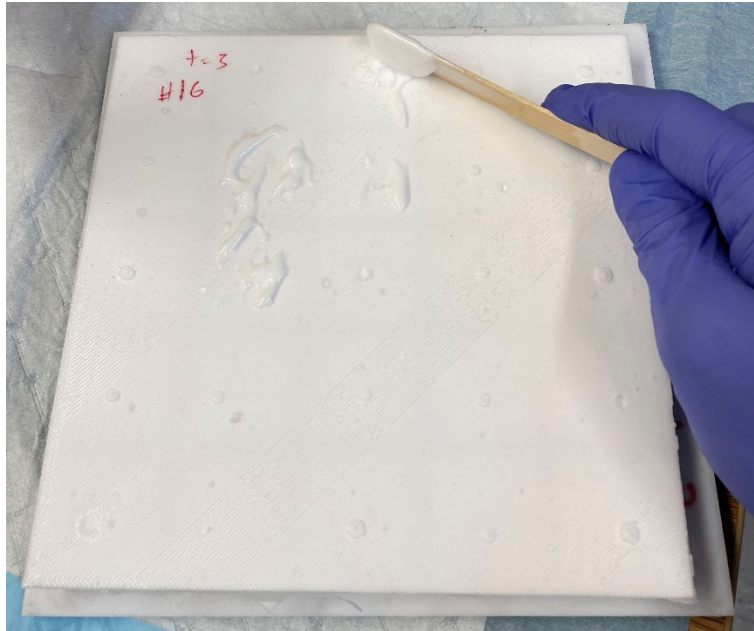


Figure 15. Filling in defects in the mold.

Once the defects were filled in, and baked for additional two hours, the piece was put aside in a box to protect it, and more insulating pieces were produced. In total, there were 21 R5 molds (smaller radius of curvature for pieces like the arms and legs) made and 18 R1 molds (larger radius of curvature for pieces like the chest and back) made with the 3 mm backing.

B. WETSUIT FABRICATION

Coordination with Cricket at Otter Bay Wetsuits in Monterey, California was required to be measured for a custom 3 mm wetsuit shell. Issues in the supply chain due to COVID and Cricket being in high demand made this early visit necessary. The double insulated, glass microsphere design was dubbed the K-Suit MK 5 and required careful planning from the start. Figure 16 shows the finished suit without the molds installed.



Figure 16. The finished 3 mm shell on which the molds are placed.

Once all the pieces were complete, they were taken to Cricket's shop for preplacement. This included placing them on the 3 mm shell of the suit and drawing an outline of where the pieces would go. It is important to ensure there is very little loose material in the shell to prevent any water from entering the suit. In addition to excess water entering the suit from loose fitting, water also entered from the wrists and ankles in previous designs. To prevent this, Velcro clasps were added to tighten the cuff area in the ankles, wrists, and neck. Equally as important is not to follow blindly a previous suit design because every body shape is different. One might need one less row of chocolate bar mold in the leg but an extra row in the abdomen. Careful thought needs to be taken when designing the spots where the molds are placed. For instance, if the molds are placed on both sides of the calf, it would be nearly impossible to get a leg through the suit. Each mold was placed on the suit and outlined prior to permanent installation as seen in Figure 17.



Figure 17. Preplacing the pieces on the suit for maximum coverage.

With double the number of pieces in each pocket, the force experienced by the pocket material increased. To prevent extra wear on the seams of the pocket, pre-curving the pieces was required. This was accomplished by curving the pieces over the cardboard roll which the neoprene material was shipped on in Cricket's shop. Then Gorilla Tape was applied to the back of the piece to help maintain the desired shape as seen in Figure 18 and Figure 19.



Figure 18. Pre-curving the pieces over the cardboard roll.

When pieces were cut into specific sizes, it became evident that taping the backs of the pieces prevented sharp corners from rubbing against the wetsuit and increased the physical integrity of the piece when the cut was on the diagonal. This method was applied to most pieces, adding duct tape to increase the strength of the piece and decrease the number of sharp edges.

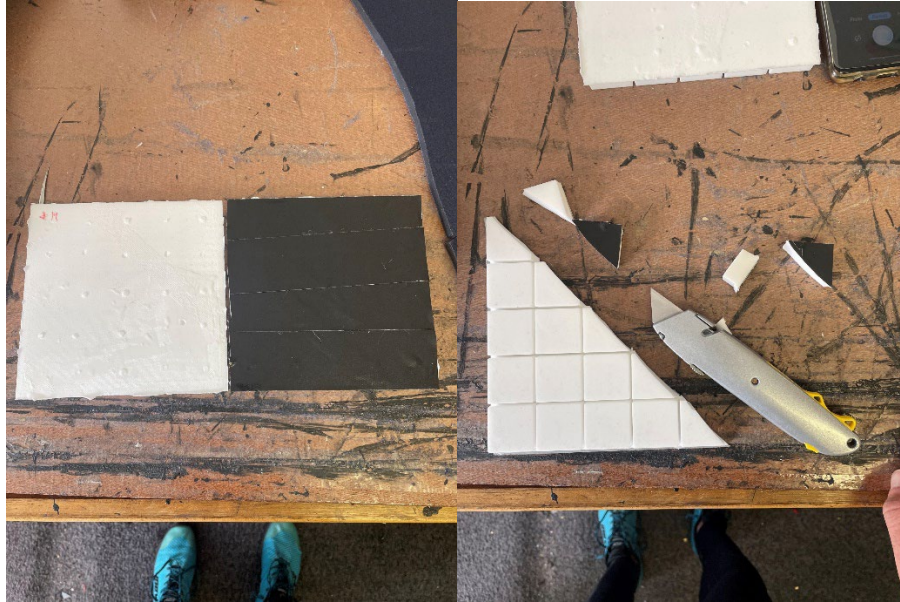


Figure 19. The process of taping and cutting the mold.

Once the pieces were preplaced and drawn on, it took a few weeks to glue them all on. As previously mentioned, the corners created by using two molds in each pocket were troublesome. The previous models of the suit, with only one mold in the pocket, claimed that water entered the pockets because the glue failed and caused issues with the suit's performance. To prevent this water intrusion, while adding two molds per pocket, Cricket used Aquaseal to add an external layer of waterproof glue to the seams of the pockets. This added a resiliency to the suit that was not seen before. After applying the Aquaseal to the seams, the suit was complete and is shown in Figure 20.



Figure 20. The complete front and back of the suit.

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IV. TESTING AND PERFORMANCE

A. EXPERIMENTAL

Dives were conducted in the local Monterey Bay waters to test the MK-5 K-Suit in sea water. Because the testing occurred during the winter months, careful planning was required to conduct safe dives. The winter months in Monterey often produce high winds and rough sea state as well as currents. To further complicate the testing window, during January of 2023, the historic atmospheric river brought record breaking amounts of precipitation to the area causing an even shorter testing window.

When the seas allowed, dives were conducted in the maximum allowed safe depth with a competent diving partner. The same control diver wore different styles of commercially available suits to provide a variety of data to compare to the MK-5. The control and MK-5 diver both wore an OMEGA OM-CP-PRTEMP1000 data loggers around their necks such that they hung in the center of their chest under the suit. These data loggers record temperature and pressure at 15 second intervals for data analysis. Each diver also wore a data recorder in a mesh pocket on their buoyancy compensator device to record the ambient water temperature. The data loggers were manually started with a computer on the dive side prior to conducting the dive as seen in Figure 21. It is imperative that one verifies the intervals of the data recording are the same (15 seconds) prior to starting them, otherwise it makes the data analysis challenging. In the past, other divers have attempted to start the devices on a timer system so that they all start at the same time however, some of the data loggers didn't start, causing a loss of data [11].



Figure 21. The Omega data logger connected to the computer. Source: [11].

Biometric data was taken for each of the divers involved in the dive test. This was taken from using the ES-26M-W Smart Body Analyzer. This data was taken to help analyze the dive results since body composition can affect the thermal insulation of the body and thus the difference of temperature from the inside to the outside of the suit. The delta from the inside and outside of each suit and then the difference in deltas between suits is the preferred comparative technique. The biometrical data for the control diver can be seen in Figure 22 and the biometrical data for the K-Suit MK 5 diver is in Figure 23.



Figure 22. Biometric data for the control diver. Source: [11].



Figure 23. Biometric data for the K-Suit MK-5 diver.

B. GEAR MAINTENANCE

Tracking down and understanding the maintenance status of all the gear proved difficult. Due to the previous students having different preferences in dive shops, it could not be determined when the latest tests and inspections were done to the first stage and second stage regulators as well as the tanks. To prevent further confusion an account was started at Aquarius dive shop in Monterey, California, under the name “NPS Thesis Project.” This allowed the shop to write down all the associated serial numbers and track the maintenance of the gear as well as get all the pieces on the same maintenance schedule. As of the time of this thesis, there are three working and tested regulator setups, three buoyancy compensator devices, and many spare parts to repair these in the future.

C. DIVE 1

The first dive took place on 20 January 2023 at Whaler’s Cove in Point Lobos State Natural Reserve. They only allow ten dive teams per day in the natural reserve so getting a reservation was key. The control diver wore a XCEL Wetsuit’s Men’s Thermoflex TDC Dive Full Wetsuit 7/6 mm. This is an advanced commercially available wetsuit that uses a semi dry cuff component and infrared reflecting technology. This is a high performing wetsuit and is often rented in this area to offset the cold waters. The average water temperature was 12.6 degrees Celsius and the maximum depth was 15 meter sea water. The data is displayed in Figure 24.

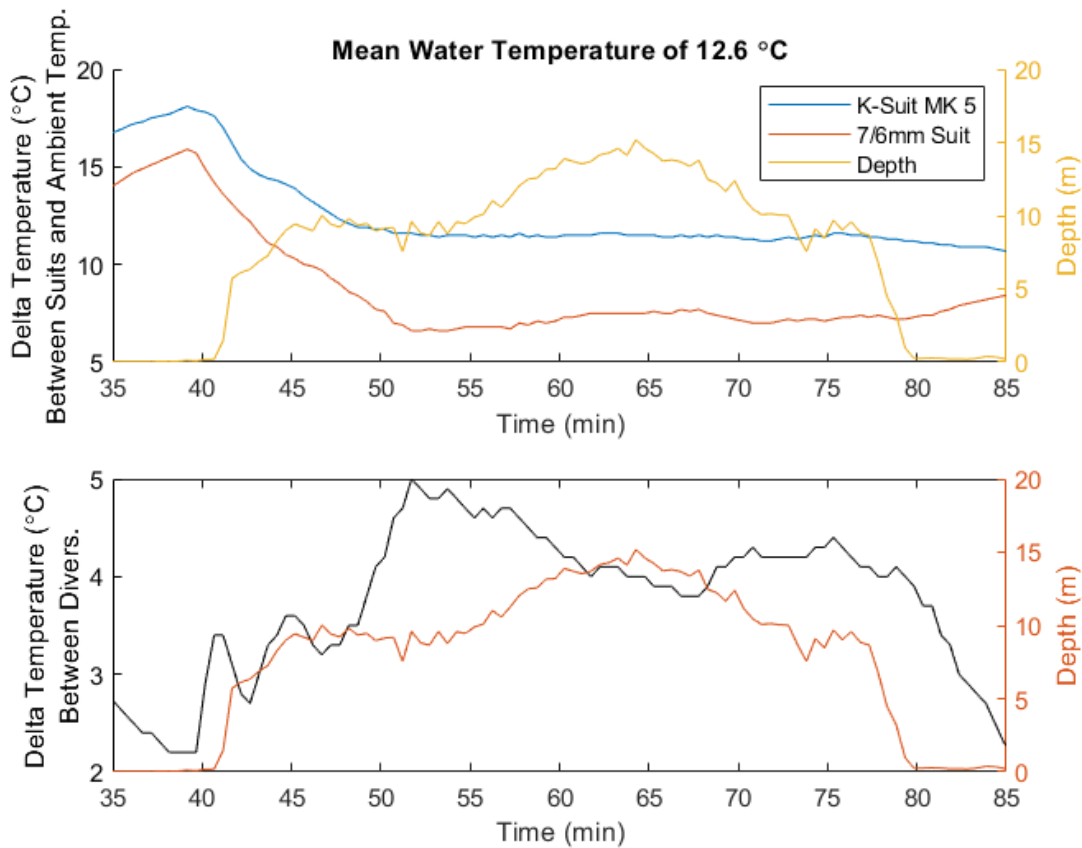


Figure 24. Dive 1 results.

The divers left the surface at approximately the 40 minute mark and arrived at depth at the 45 minute mark but the maximum difference between divers was not obtained until the 52 minute mark. This is likely attributed to the compression of the neoprene in the XCEL control wetsuit. The slow decrease in the difference between divers after the 52 minute mark is likely due to the small amount of leakage in the through the K-Suit wrist cuffs that made its way to the core. The average difference between the divers during the dive was 4.05 degrees Celsius with the K-Suit as the warmer suit and on display in Figure 25.



Figure 25. K-Suit MK 5 in action.

D. DIVE 2

The second dive took place on 02 March 2023 at San Carlos Beach in Monterey, California. The average water temperature was 1.4 degrees Celsius lower than during dive 1. The same control diver wore a 7.5 mm Yazbeck neoprene long-john style suit. This means that the pants and top are separate but cover the torso twice for a total of 15 mm of neoprene coverage over the core, and specifically where the temperature sensor was placed. The other additional advantage of the two piece long-john style suit is it does not contain a zipper which is the main source of water leakage into the suit. There were no alterations made to the K-Suit. The maximum depth achieved was 15 meters and the visibility was approximately 10-15 feet. The results are displayed in Figure 26.

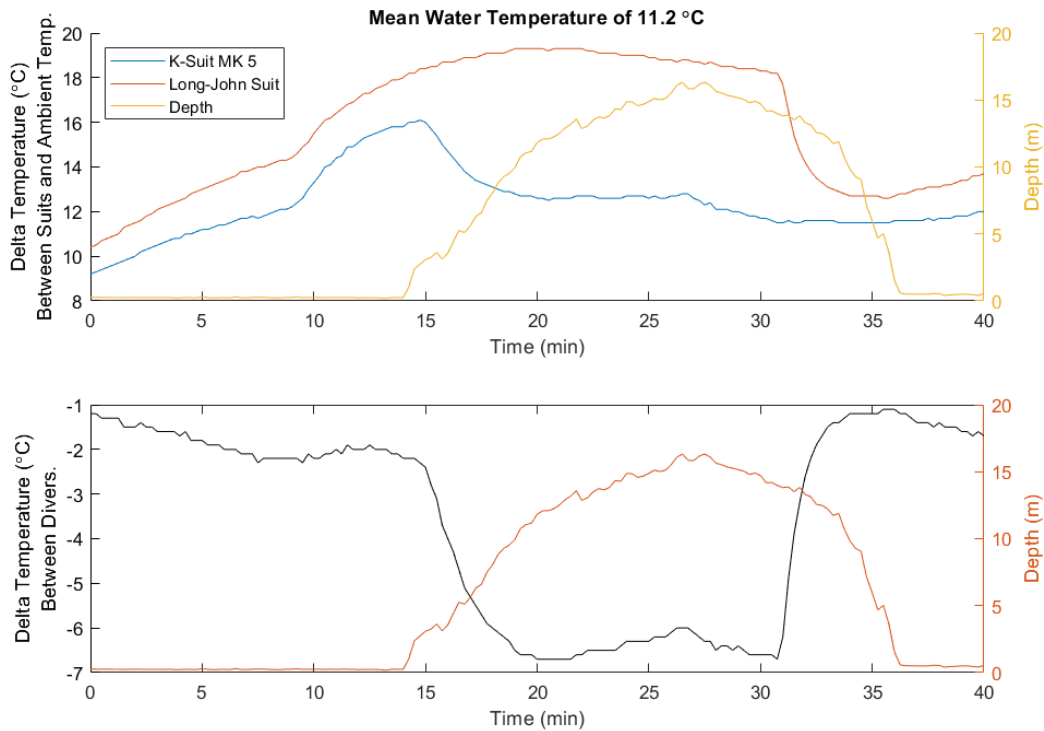


Figure 26. Dive 2 results.

The average difference between divers was -6 degrees Celsius. This was an increase in performance of 4.43 degrees Celsius in comparison to the similar test conducted in Dive 4 of Meligkaris [11] where the same control diver wore the same dive suit. At the 31 minute mark, you can see a reduction in performance of the long-john suit possibly because of the compression of the suit.

E. DIVE 3

Dive 3 was conducted on the same day and place as dive 2. The control diver switched out his long-john style suit with the Aqualung SOLAFLEX 8/7 mm wetsuit. This suit uses a few advanced features such as the neck damn and integrated hood, fleece lining, chest zipper vice back zipper, and semi-dry cuffs for the wrists and ankles. The SOLAFLEX suit is the highest performing neoprene wetsuit that Aqualung produces. Of course, this comes with the cost of reduced ergonomics of the suit due to the thick nature

of the neoprene in the arms and legs. The same average water temperature of 11.2 degrees Celsius and maximum depth of 15 meters was recorded. The results are seen in Figure 27.

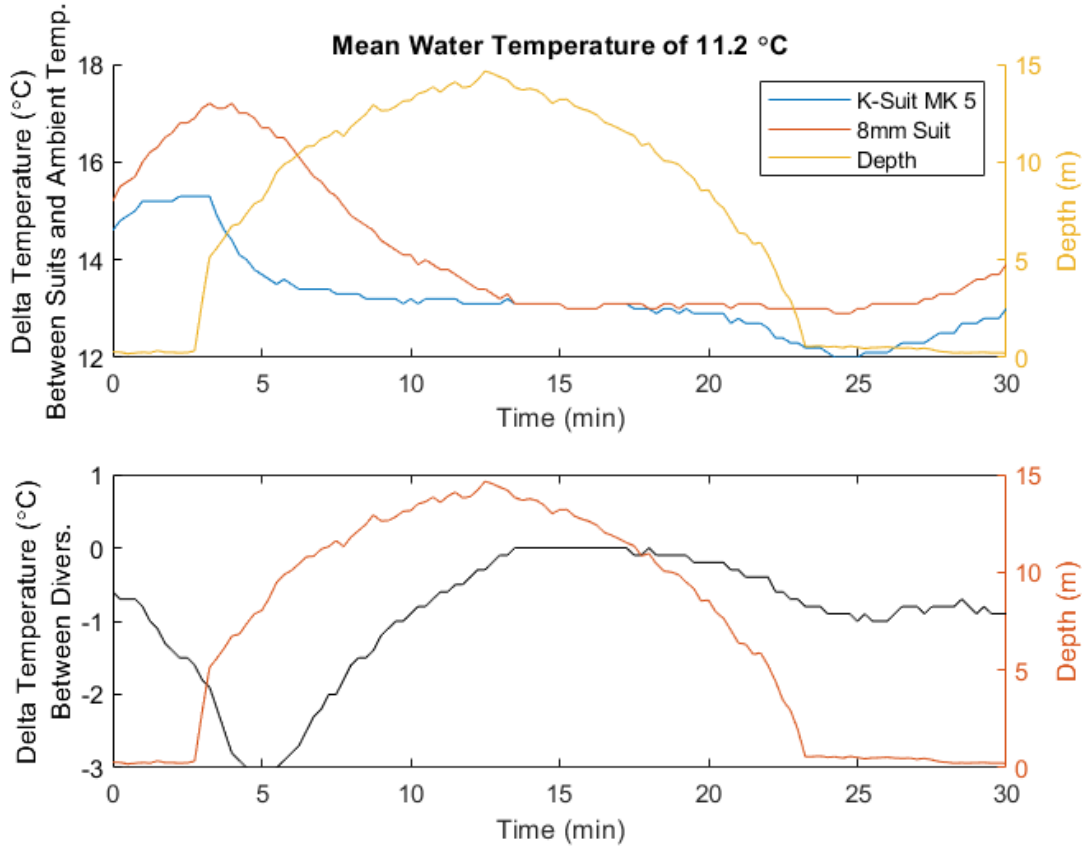


Figure 27. Dive 3 results.

The largest difference between divers occurred at the three minute mark when the divers left surface. The average difference between wetsuits during the 20 minute dive was -.94 degrees Celsius. As expected, the SOLAFLEX control wetsuit compressed almost immediately and the difference between wetsuits became nearly zero, 10 minutes into the dive. One could expect that during a longer and deeper dive, the trend would continue, and the K-Suit would become thermally, and obviously ergonomically, superior.

F. FUTURE DIVE TESTING

With completion of these three dive tests, this concludes the planned testing phase of the K-Suit. The three control wetsuits tested against are the most typical type of neoprene wetsuits used during cold water diving. The next step would be to test against a dry suit. The dry suit does not allow any water to penetrate it and can include heating elements on the inside to assist in heating the diver. This test dive would likely prove the dry suit thermally superior. However, the K-Suit is not made to replace the dry suit.

Dry suits have many negatives, they are the leading cause of the dive related illnesses caused in the Navy because of the challenging buoyancy compensation. They also are very prone to cutting, rendering them useless, and require special certifications in which to dive. For these reasons, the K-Suit is not a replacement for the dry suit but a better option for most diving operations with exception of extreme diving situations such as under ice.

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V. CONCLUSION AND RECOMMENDATION

A. CONCLUSION

The goal of this research was to further the design of previous K-Suit models. The research proved that doubling the amount of insulation would improve the thermal performance of the K-Suit while maintaining the ergonomics at the standard 3 mm level using the chocolate bar design over the body-specific molds. In addition there were improvements in the mold manufacturing phase and the wetsuit fabrication design.

The improvements in the manufacturing phase reduced many man hours in the lab and improved the quality assurance of the pieces. Reducing the amount of air bubbles in each piece and their likelihood of breaking while removing the pieces from their molds, improved their thermal efficiency in the suit as well as the efficiency of creating the pieces.

The K-Suit MK 5 outperformed all control wetsuits in the ergonomics category. It also out performed the 7/6 mm wetsuit thermally and was on par with the 8/7 mm wetsuit thermally with the hypothesis that it would surpass the 8/7 mm wetsuit on a longer or deeper dive due to the neoprene compression. It did not outperform the 7.5 mm long-john style suit thermally, due to the 15 mm of neoprene coverage on the chest but did make significant improvements from the K-Suit MK-5 in comparison against the long-john style suit (4.43 degrees Celsius) [11].

B. RECOMMENDATIONS FOR FUTURE PROJECTS

- Recommend starting with a commercially available 3 mm wetsuit that comes with semi dry cuffs, taped seams, neck-dam and integrated chest zipper. This style of wetsuit will greatly reduce the chance of any water penetrating the weaknesses of the suit. The pads on the custom-made wetsuit might be causing extra leakage because it is a nonstandard design.
- Recommend using standard hair conditioner to lubricate the inside of the suit prior to putting it on and having a fellow diver assist in getting into the suit. The K-Suit pads make it more challenging to put on the diver than

a typical wetsuit and the conditioner reduces the time to get into the suit by over one half.

- Recommend making the next version of the wetsuit with the double chocolate bar design to reduce production time and universal fitting. However, make one layer of the glass microsphere design, and one layer of the ceramic design from Meligkaris [11]. I had to wear 30 pounds of lead weight to maintain neutral buoyancy which is unreasonable and the ceramic layer will help with offsetting the buoyancy issue.
- Recommend skipping the 7/6 mm wetsuit test since all recent versions outperform it. Instead, specifically plan a deep, 40 minute dive with the 8/7 mm wetsuit as the control suit.
- Recommend using the newer, smaller data loggers on the chest to minimize the obstruction and air pocket in the suit to increase thermal efficiency.

LIST OF REFERENCES

- [1] *U.S., Navy Diving Manual*, 7th ed., Washington, DC, USA: Naval Sea Systems Command, 2016.
- [2] Engineering ToolBox, “Air – Thermal conductivity vs. temperature and pressure.” https://www.engineeringtoolbox.com/air-properties-viscosity-conductivity-heat-capacity-d_1509.html (accessed Jan. 10, 2023).
- [3] J. S. Hayward, J. D. Eckerson, and M. L. Collis, “Thermal balance and survival time prediction of man in cold water,” *Can. J. Physiol. Pharmacol.*, vol. 53, no. 1, pp. 21–32, Feb. 1975, doi: 10.1139/y75-002.
- [4] M. B. Ducharme and D. S. Lounsbury, “Self-rescue swimming in cold water: The latest advice,” *Appl. Physiol. Nutr. Metab.*, vol. 32, no. 4, pp. 799–807, Aug. 2007, doi: 10.1139/H07-042.
- [5] M. Volker, “Cold water survival,” *Seo Title*, Jul. 08, 2022. https://ussartf.org/cold_water_survival.htm (accessed Jan. 10, 2023).
- [6] K. Rutledge et al., “Wetsuit,” *National Geographic*. <https://education.nationalgeographic.org/resource/wetsuit> (accessed Jan. 10, 2023).
- [7] J. M. Brown, “Microsphere-based passive material for low-temperature diving suits,” M.S. thesis, Dept. of Physics, NPS, Monterey, CA, USA, 2018 [Online]. Available: <https://apps.dtic.mil/sti/pdfs/AD1059776.pdf>
- [8] A. P. Demers, “Depth independent thermal insulation for diving suits,” M.S. thesis, Dept. of Physics, NPS, Monterey, CA, USA, 2020 [Online]. Available: <https://apps.dtic.mil/sti/pdfs/AD1114573.pdf>
- [9] S. L. Martin, “Building and testing an incompressible thermally insulating cold temperature diving wetsuit,” M.S. thesis, Dept. of Physics, NPS, Monterey, CA, USA, 2020 [Online]. Available: <https://apps.dtic.mil/sti/pdfs/AD1126514.pdf>

- [10] A. Waldron, "Improving the flexibility and thermal protection of a diving wetsuit," M.S. thesis, Dept. of Physics, NPS, Monterey, CA, USA, 2022 [Online]. Available: <https://apps.dtic.mil/sti/pdfs/AD1184669.pdf>
- [11] K. Meligkaris, "Design and test of a microsphere-based composite diving suit for improved tactical performance in a naval special warfare environment," M.S. thesis, Dept. of Physics, NPS, Monterey, CA, USA, 2022 [Online]. Available: <https://calhoun.nps.edu/handle/10945/71510>

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