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DESIGN AND TEST OF A MICROSPHERE-BASED COMPOSITE DIVING SUIT FOR IMPROVED TACTICAL PERFORMANCE IN A NAVAL SPECIAL WARFARE ENVIRONMENT

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THESIS

DESIGN AND TEST OF A MICROSPHERE-BASED COMPOSITE DIVING SUIT FOR IMPROVED TACTICAL PERFORMANCE IN A NAVAL SPECIAL WARFARE ENVIRONMENT

by

Konstantinos Meligkaris

December 2022

Thesis Advisor:	Emil P. Kartalov
Co-Advisor:	Leo J. Blanken

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Naval Special Warfare (NSW) operators are required to dive into cold waters for a prolonged time to infiltrate demanding environments. While underwater vehicles give the opportunity for longer infiltration ranges and deeper dives, the diving suit, which protects the diver from hypothermia, becomes the most essential diving equipment for the success of the mission. Although the first wetsuit was made in the 1950s, there has been no significant advancement in the neoprene material until recently, and the shrinking neoprene air pockets under depth pressure decrease the thermal insulation of the wetsuit and affect the diver’s buoyancy. To overcome this downside, the K-Suit Mk.4 prototype was created to give NSW operators an alternate diving wetsuit option with superior ergonomics, depth-independent thermal insulation and buoyancy, and possible sound protection. This wetsuit has a base layer of 3mm neoprene and two layers of composite materials. The first composite layer is composed of 8mm-thick glass microspheres mixed with a polymer and the second is thinner and forms solid ceramic beads coupled with the same polymer. Six experimental dives were carried out to gather temperature and pressure data. The data were analyzed, and the result is the K-Suit has the ability to outperform the traditional 7mm diving wetsuit specifications that NSW typically uses.

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Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN APPLIED PHYSICS

and

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(IRREGULAR WARFARE)**

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ABSTRACT

Naval Special Warfare (NSW) operators are required to dive into cold waters for a prolonged time to infiltrate demanding environments. While underwater vehicles give the opportunity for longer infiltration ranges and deeper dives, the diving suit, which protects the diver from hypothermia, becomes the most essential diving equipment for the success of the mission. Although the first wetsuit was made in the 1950s, there has been no significant advancement in the neoprene material until recently, and the shrinking neoprene air pockets under depth pressure decrease the thermal insulation of the wetsuit and affect the diver's buoyancy. To overcome this downside, the K-Suit Mk.4 prototype was created to give NSW operators an alternate diving wetsuit option with superior ergonomics, depth-independent thermal insulation and buoyancy, and possible sound protection. This wetsuit has a base layer of 3mm neoprene and two layers of composite materials. The first composite layer is composed of 8mm-thick glass microspheres mixed with a polymer and the second is thinner and forms solid ceramic beads coupled with the same polymer. Six experimental dives were carried out to gather temperature and pressure data. The data were analyzed, and the result is the K-Suit has the ability to outperform the traditional 7mm diving wetsuit specifications that NSW typically uses.

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LIST OF ACRONYMS AND ABBREVIATIONS

dB	deciBel
DCS	Decompression Sickness
EOD	Explosive Ordnance Disposal
EID	External Internal Defense
FSW	Foot Sea Water
GPC	Great Power Competition
LARU	Lambertsen Amphibious Respiratory Unit
NAB	Naval Base
NEDU	Naval Experimental Diving Unit
NSMRL	Naval Submarine Medical Research Laboratory
NSW	Naval Special Warfare
PDMS	PolyDiMethylSiloxane
PEL	Permissible Exposure Limit
PSI	Pounds per Square Inch
SCUBA	Self-Contained Underwater Breathing Apparatus
SDV	Seals Delivery Vehicle
SEAL	Sea, Air, and Land
SONAR	SOund Navigation And Ranging
SPL	Sound Pressure Level
UDT	Underwater Demolition Team
UUV	Underwater Unmanned Vehicle

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EXECUTIVE SUMMARY

Naval Special Warfare (NSW) operators must overcome several challenges in the hostile environment of sea water in order to accomplish their mission. Their operational skills are impacted by hypothermia, which has the potential to cause unconsciousness and, eventually, death. Thermal protection is therefore essential to safely provide NSW operators access to deeper dives and longer infiltration distances. Typically, standard neoprene wetsuits are used to protect divers from the cold. Since its invention in the 1950s, neoprene technology has essentially not changed, and its main flaw is that air pockets shrink when put under pressure. As a result, a wetsuit's ability to provide thermal insulation deteriorates at deeper depths, which also affects the diver's buoyancy. Additionally, thicker wetsuits offer greater thermal insulation but compromise flexibility and cause more buoyancy fluctuation as divers go deeper.

In order to provide NSW operators with an alternative diving wetsuit solution with greater ergonomics, depth-independent thermal insulation and buoyancy, and perhaps underwater sound protection, this thesis presents the fabrication of an innovative composite wetsuit prototype. Such a solution would provide safer dives and advanced operational capabilities.

For the K-Suit Mk.4 development, we created a composite material with hollow glass microspheres embedded in silicone carrier polymer to address the shrinking issue. Next, we overlaid a thinner layer of composite material comprised of solid ceramic microspheres that were embedded in silicone, which helps maintain the wetsuit neutrally buoyant while distributing weight. Moreover, we believe that the ceramic layer protects the human body from underwater sound waves better than the typical neoprene wetsuit. Finally, the two-layer segments were attached to a 3mm neoprene suit and held in place by tiny pockets of neoprene that were externally adhered to the suit. Since flexibility is necessary for ergonomics and the composite materials were less flexible than neoprene, the composite plates were divided at the key joints of the body to enable the suit to bend readily when needed.

The performance of K-Suit was evaluated in the field and compared with various configurations of commercial wetsuits. More precisely, dataloggers were utilized to record the temperature and pressure within the wetsuit throughout six dives. In terms of flexibility and weight distribution, K-Suit performed better than all of the competitors. It also showed less vulnerability to thermal performance decrease with depth than the neoprene systems. Finally, the relative thermal protection performance surpassed 5mm wetsuits and was nearly on level with the 7mm wetsuit which typical worn by NSW operators.

Future deep dives might be conducted to compare the K-Suit Mk.4 to a conventional 7mm wetsuit and come to reliable findings about the superiority and incompressibility of the K-Suit. In-depth research addressing the sonar protection offered by solid ceramic composite pieces must also be conducted. Other materials, such as hollow ceramic beads, could also be evaluated. Thinner composite layers that are more flexible and cover larger regions might be used to create a wetsuit that provides the same level of thermal insulation. Those beads are more comparable to neutral buoyancy but slightly less effective in terms of thermal insulation than hollow glass microsphere beads.

ACKNOWLEDGMENTS

Firstly, I would like to thank the Hellenic Navy, which gave me the opportunity to attend a master's degree program, and I will do my best to provide a big part of my knowledge back. Moreover, I want to express my gratitude to the U.S. Navy for the hospitality at the historic Naval Postgraduate School and the loveliness of Monterey.

I would like to acknowledge my beloved father, who introduced me to the high seas, my lovely mother who taught me to study hard, and the Hellenic Naval Special Forces Command, which trained me in challenging dives and taught me always to accomplish my goals; this is how I came to choose this thesis.

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I. INTRODUCTION TO DIVING AND DIVING SUITS

Divers in ages past explored the waters for many of the same reasons as contemporary divers do today: to get food, seek valuables, perform scientific exploration, enjoy the underwater environment, carry out ship maintenance, and conduct military operations.

A. HISTORY OF DIVING

Free diving is the oldest and most straightforward technique, used mostly for gathering food and treasure. Swimming was an essential ability for a diver in the Stone Age, according to contested Neolithic rock drawings discovered at the Cave of Swimmers in South-Western Egypt [1]. Archaeologists have also discovered shells and pearls that could only have been acquired by diving in Mesopotamia and Egypt between 4500 and 2400 BCE [2]. However, Homer's epic poem "The Iliad," which dates back to the eighth century BCE, has descriptions of diving practices that are the first diving activities referenced in literature [2]. It narrates older stories from divers who participated in the Trojan War in the 13th century BC and also mentions sea sponges that could have been gathered only by diving [3]. The most well-known sponge divers came from Kalymnos, a Greek island. As shown in Figure 1, they employed a free-diving technique in which the diver would fasten a length of rope to himself and attach a round stone known as a "skandalopetra" to it to serve as a weight. When he reached the sea floor, he would release the skandalopetra, collect the sponges, and then signal the men in the boat to haul him to the surface [4]. At the time, there were no underwater breathing apparatuses other than hollow reeds, and swimmers dove naked without any protection [5].

The first type of underwater breathing systems which also protected divers were the diving bells. This means of underwater respiration is referenced in Aristotle's writings when he discusses the renowned "Λέβης," a large boiler that was driven directly into the water and retained air [6]. However, the first device considered a true diving bell was developed in 1535 by Guglielmo de Lorena [5]. Early diving bells limited the diver's movement even if they offered some protection and a finite amount of air. As a result, to make salvage operations more effective required the development of a more advanced diving uniform [7]. In the 17th and 18th centuries a variety of devices had been invented to provide divers with air and to allow increased mobility. However, Augustus Siebe's invention of the diving suit in 1819—a jacket with a metal helmet attached to the collar and a hose allowing a continual supply of air to the diver—marked the first significant step toward the creation of successful surface-supported and protected diving system [5].

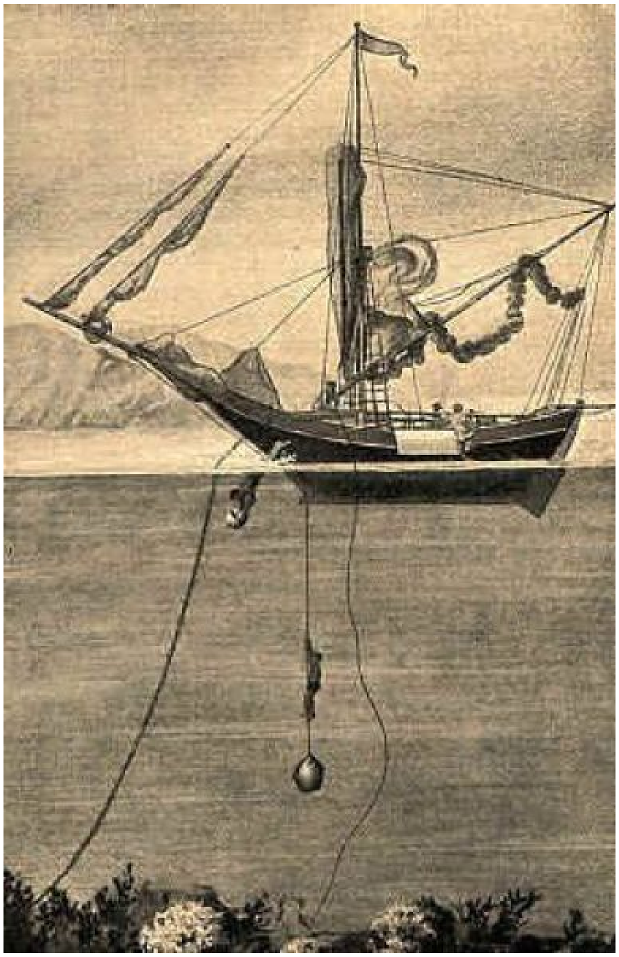


Figure 1. Naked Greek Sponge Diver Using Skandalopetra Technique. Source: [4].

Hard-hat gear did not undergo any significant advancements until 1905, when the U.S. Department of Construction and Repair created the iconic MK-V diving rig depicted in Figure 2, to overcome many of the issues with prior diving helmets and rigs [8]. The

MK-V breakthrough allowed U.S. divers to work in polluted waters as well as at significantly deeper depths [8]. Morse and Schrader produced the first U.S. Navy Mark V helmets, which were utilized by the U.S. Navy from 1916 until 1984, when the fiberglass Mark XII ultimately took over permanently [9].

Figure 2. Navy Diver George McCullough Wears an MK V Diving Rig.
Source: [8].

In 1943 contemporary demand regulators for underwater diving were created by Jacques-Yves Cousteau and Emile Gagnan [10]. Their "Aqua Lung" innovation laid the groundwork for the contemporary self-contained underwater breathing apparatus

(SCUBA) and isolated the breathing devices from diver’s thermal insulation and protection suit.

B. DIVING THREATS

Various dangers lurk in the underwater environment, including hazardous aquatic species, polluted waters, equipment malfunctions, illness caused by improper use of breathing apparatus (determined by type of air, dive duration, and depth), a “loud” underwater environment, and frigid waters. Furthermore, diving in deeper seas becomes more challenging and requires extensive training as well as specialized equipment. Divers can be protected or assisted in avoiding some underwater dangers by wearing diving suits.

1. Hazardous Aquatic Species

Divers may encounter certain aquatic creatures that are dangerous. While few pose major physical risks, certain creatures might cause discomfort, trigger an allergic response, or cause another injury that can worsen a diver’s ability. Naked divers are exposed to even more allergens and more apparent hazardous species like sea jellies and urchins.

2. Polluted Waters

The variety of chemical substances, oil refined products, and sewage contaminating oceans has expanded over the past few decades. Although governments have implemented strict regulations and fines to prevent pollution, there are still some situations, such as naval accidents and natural disasters, where they cannot prevent pollutants. Unfortunately, there are occasions when divers cannot distinguish chemically tainted waters, or even worse, they must enter polluted waters to work on critical issues. Because standard diving suits only provide limited protection, usually diving manuals recommend the usage of specialized diving suits.

3. Decompression Sickness

By the end of the 18th century, the development of the diving bells allowed prolonged diving in deeper waters. It soon became apparent that many of the users complained of dizziness, limb or joint discomfort, and later in life, they were frequently handicapped. Because the workers' posture closely mirrored the forward-leaning posture of style-conscious women whose body carriage was known as the "Grecian bend," the complaints of the workers came to be known as "the bends" [5].

The true clinical cause of "the bends" was established by French scientist Paul Bert in 1878, who also found that inhaling air under pressure caused quantities of nitrogen to dissolve in the body's blood and tissues [11]. While the pressure persists, the gas remains in solution; however, when it abruptly releases, the nitrogen swiftly reverts to a gaseous state, leaving the body too quickly to disappear naturally.

The development of decompression timetables was a significant advancement in diving concerning preventing decompression sickness. U.S. Navy divers seldom descended below 60 FSW prior to 1912 [7]. Chief Gunner George D. Stillson established a program to evaluate diving tables and stage decompression techniques that year. The U.S. Navy Divers advanced in depth over three years, finally reaching 274 FSW, and after a few months, were dramatically brought to use when the USS F-4 sunk [7]. After 15 years of submarine operations, it was the first lost ship, and the Navy Divers undertook a significant salvage operation to retrieve the 21 bodies that had been lost.

Divers today employ sophisticated dive computers and well tested diving timetables to prevent decompression sickness. The two major methods for avoiding decompression sickness are ascending at the proper pace and adhering to the dive time recommendations. However, five other factors may contribute to individual susceptibility: activity, heat stress, post dive air travel, medical and physical fitness, and the breathing gas mixture [12]. A diving suit that keeps the diver warm while simultaneously allowing for mobility, aids in the body's ability to absorb more inert gas, release it more quickly, and reduce workload, all of which can significantly reduce the risk of DCS for divers.

4. Underwater Sounds and Explosions

Over the previous few decades, technology advances such as military sonars have spread to the civilian sector, contributing to a "louder" undersea environment. Small power explosions also occur accidently, such as from welding in gas-filled places or handling unexploded ordnance, as well as intentionally, such as when people cut cables or chains, demolish natural formations, or engage in illegal fishing. Both elements have the potential to have an adverse effect, harm, or even kill marine mammals and of course divers even large distances away from the source [7].

There are several formulae available for calculating the pressure produced by an explosion wave. Scaling regulations created by the Naval Ordnance Lab in White Oak, Maryland, are still widely used today. After rising, it is expected that the shock pressure would then exponentially decrease, with the peak overpressure Pmax being determined as shown in Equation (1) [13]:

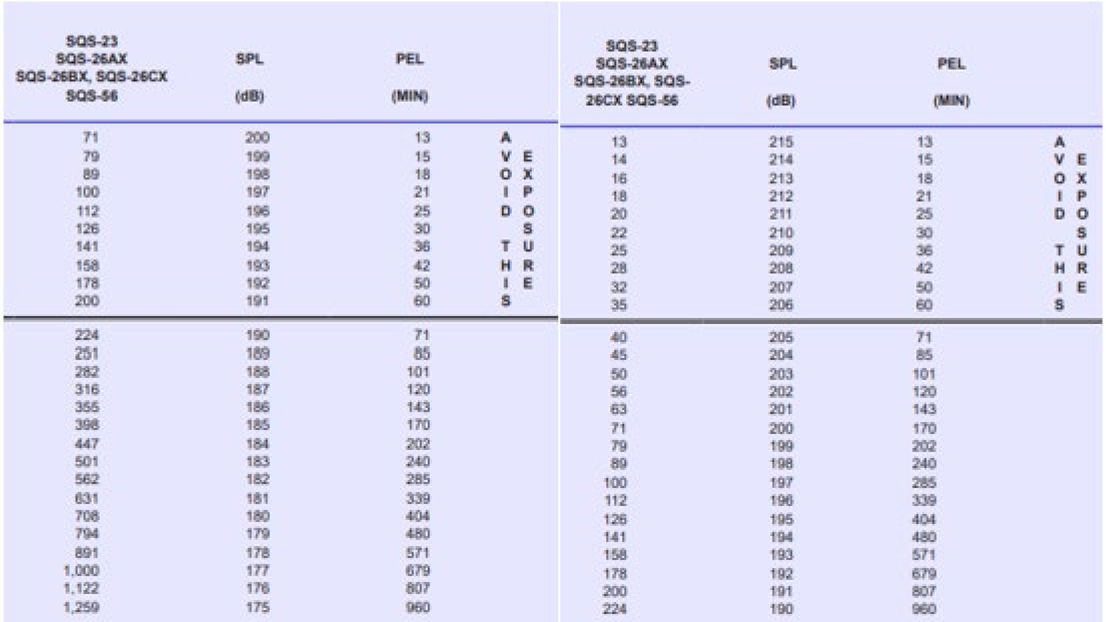
$$Pmax = 7{,}600\left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.18} \quad , \tag{1}$$

where W is the underwater explosive's TNT equivalent mass in kilograms, R is its slant distance from the explosion spot, and Pmax is measured in pounds per square inch. Explosion pressure waves are most damaging to the parts of the body which contain air pockets, so the head, lungs, and intestine are the most vulnerable regions of human body [14]. The U.S. Navy Diving Manual advises divers to keep the pressure they encounter from an explosion to less than 50 pounds per square inch if they are unable to escape its effects [7].

As already mentioned, underwater noises are produced by sonars, and their "loudness" is often determined by their amplitude and connected to sound pressure. The local pressure difference from the surrounding pressure created by a sound wave is known as sound pressure and measured in (Pa) [15]. Sound Pressure Level (SPL) is the logarithmic expression of the "effective pressure of a sound relative to a reference value," measured in decibel (dB) by the Equation (2)

$$SPL = 20\,log_{10}\left(\frac{P_{rms}}{P_{ref}}\right) \quad , \tag{2}$$

where P_{rms} is the root mean square sound pressure in (Pa), and the Pref is the reference sound pressure in (Pa) [15]. The Naval Submarine Medical Research Laboratory (NSMRL) and Naval Experimental Diving Unit (NEDU) undertake research to develop the Permissible Exposure Limit (PEL), which is used in the U.S. Diving Manual [7]. Those limits are calculated for specific omni-radiated sonars at various SPLs to provide the safe exposure time within a 24-hour period, but as shown in Figure 3 they vary depending on whether divers wear a helmet wetsuit hood or nothing [7].



SQS-23 SQS-26AX SQS-26BX, SQS-26CX SQS-56	SPL (dB)	PEL (MIN)	
71	200	13	A
79	199	15	V E
89	198	18	O X
100	197	21	I P
112	196	25	D O
126	195	30	S
141	194	36	T U
158	193	42	H R
178	192	50	I E
200	191	60	S
224	190	71	
251	189	85	
282	188	101	
316	187	120	
355	186	143	
398	185	170	
447	184	202	
501	183	240	
562	182	285	
631	181	339	
708	180	404	
794	179	480	
891	178	571	
1,000	177	679	
1,122	176	807	
1,259	175	960	

SQS-23 SQS-26AX SQS-26BX, SQS-26CX SQS-56	SPL (dB)	PEL (MIN)	
13	215	13	A
14	214	15	V E
16	213	18	O X
18	212	21	I P
20	211	25	D O
22	210	30	S
25	209	36	T U
28	208	42	H R
32	207	50	I E
35	206	60	S
40	205	71	
45	204	85	
50	203	101	
56	202	120	
63	201	143	
71	200	170	
79	199	202	
89	198	240	
100	197	285	
112	196	339	
126	195	404	
141	194	480	
158	193	571	
178	192	679	
200	191	807	
224	190	960	

Ranges for unhooded divers (left), ranges for divers wearing wetsuit hood (right).

Figure 3. Estimated Ranges in Yards for Given SPL and PEL for Specific Sonar Types. Source: [7].

Neoprene is a particularly effective sound absorber due to its porous nature because the air pockets within interact through friction and dissipate energy as heat [15]. Thus, typical diving suits provide not only SPL reduction capabilities, but also partial protection from explosions' wave pressure, especially in sensitive organs such as ears [16].

5. Hypothermia

Maintaining body temperature is crucial for all metabolic and vital processes. Humans generally have a steady body temperature; however, it can be reduced or increased by a variety of internal and environmental factors [17]. For example, water has a specific heat that is about four times greater than air, and heating a layer of water that is in direct contact with the skin results in a far greater loss of body energy than heating a layer of air

[18]. Moreover, heat can be conducted through water, even when the water is not flowing. In comparison to air, the rate of heat conduction in water is around 27 times quicker [18]. Thus, the diver's body temperature reduces significantly more rapidly underwater due to the higher thermal conductivity and specific heat of water compared to air. As a result, several institutes have been attracted to investigate underwater hypothermia and generate diagrams forecasting predicted survival times, as seen in Figure 4 [17].

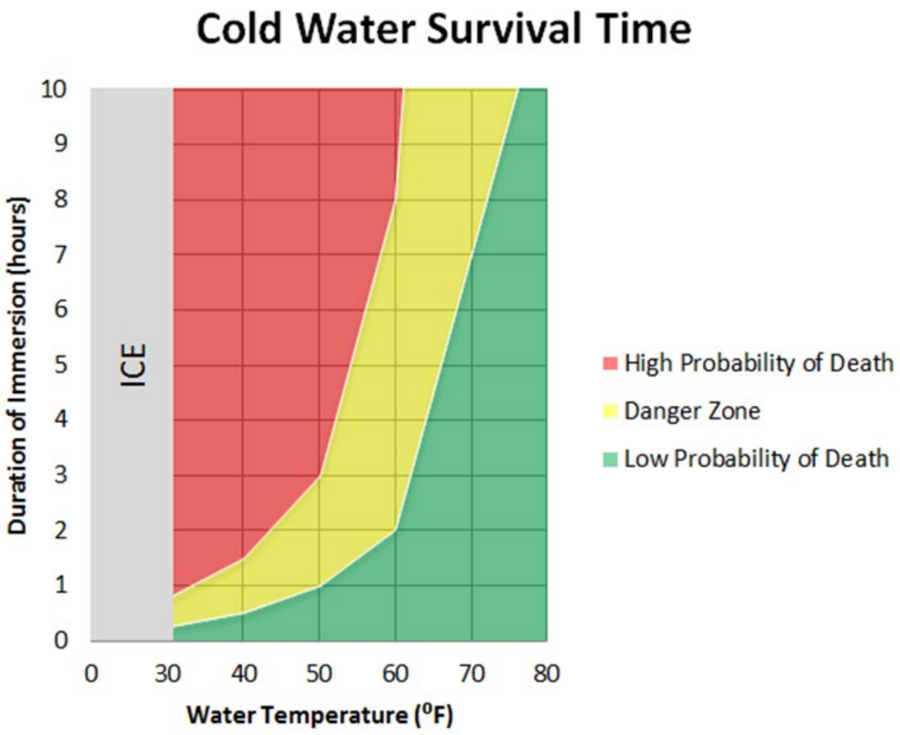
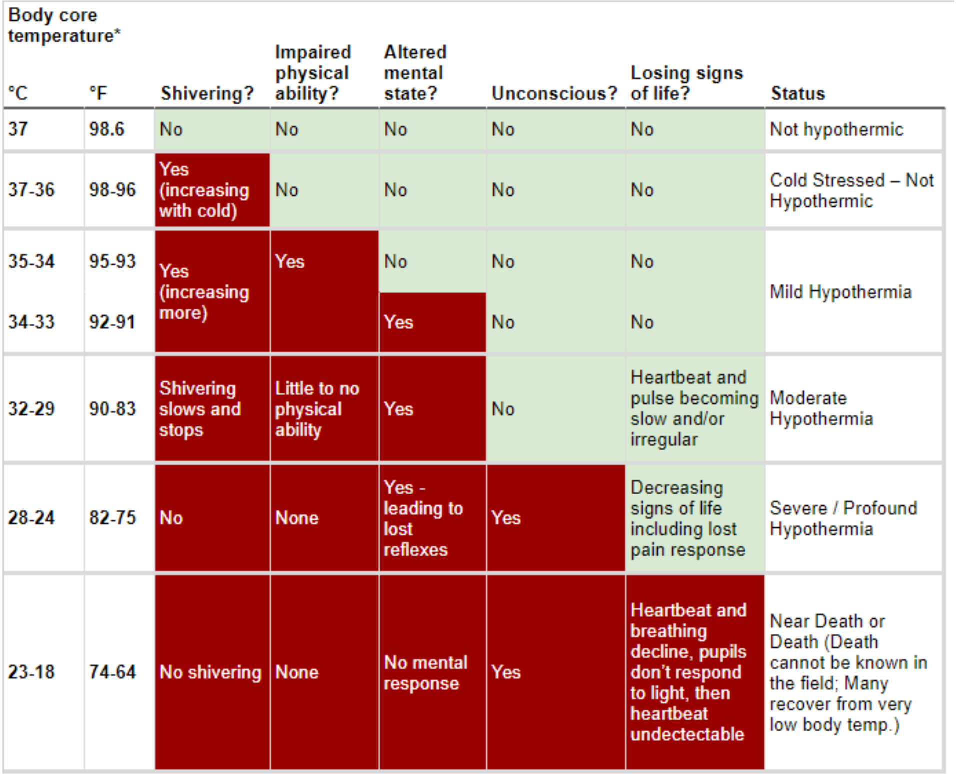


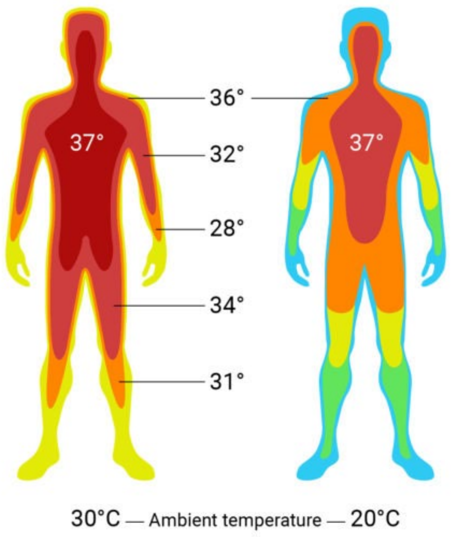
Figure 4. Expected Survival Time in Cold Water. Source: [19].

As seen in Figure 5, hypothermia progresses through multiple phases, starting out mildly when the body core temperature falls below 96° F and becoming fatal below 75° F [20]. At this point it is important to distinguish core body temprature from body shell temperature which might feel colder faster, since it is being affected directly by ambient temperature, as depicted in Figure 6 [17].



Body core temperature*							
°C	°F	Shivering?	Impaired physical ability?	Altered mental state?	Unconscious?	Losing signs of life?	Status
37	98.6	No	No	No	No	No	Not hypothermic
37-36	98-96	Yes (increasing with cold)	No	No	No	No	Cold Stressed – Not Hypothermic
35-34	95-93	Yes (increasing more)	Yes	No	No	No	Mild Hypothermia
34-33	92-91			Yes	No	No	
32-29	90-83	Shivering slows and stops	Little to no physical ability	Yes	No	Heartbeat and pulse becoming slow and/or irregular	Moderate Hypothermia
28-24	82-75	No	None	Yes - leading to lost reflexes	Yes	Decreasing signs of life including lost pain response	Severe / Profound Hypothermia
23-18	74-64	No shivering	None	No mental response	Yes	Heartbeat and breathing decline, pupils don't respond to light, then heartbeat undectectable	Near Death or Death (Death cannot be known in the field; Many recover from very low body temp.)

Figure 5. Hypothermia Stages. Source: [20].



The body's core temperature typically remains constant, although the body's outer layer is affected by both internal and external factors.

Figure 6. Body's Temperature Distribution Field. Source: [17].

There are many methods to reduce the risks associated with diving in general, but for the diving risks covered in this chapter, wearing the proper diving suit becomes essential. As explained, maintaining the diver's core body warmth and avoiding hypothermia's consequences are the main goals of a diving suit. Prolonged or deeper dives increase the need for a warm diving suit, which gives a diver the ability to accomplish his mission.

C. DIVING SUITS

Diving suits were first worn after the invention of diving bells during 18th century, when states wanted to develop salvage operations and make diving more efficient. In 1715, Englishman John Lethbridge created the first diving dress, which was entirely enclosed, referred to as "Lethbridge's Diving Dress" [7]. About one century later Augustus Siebe modified a patented diving dress to create "Siebe's Diving Dress and Helmet" [21]. It consisted of a heavy suit to protect against the cold, hose connections for surface-supplied air, and a sealed helmet with viewing ports, which essentially was the predecessor of the MK-V diving rig [21]. However, the first significant breakthrough that introduced the open-circuit SCUBA was the contemporary demand regulator, which Jacques Yves Cousteau and Emile Gagnan created in 1946 [10]. The "Aqua Lung" regulator gave divers the opportunity to use cheaper devices with augmented maneuverability since divers did not need to rely on air hoses that were attached to a surface source [10].

It was at this time that the diving suit began to be viewed as a separate piece of equipment from the breathing apparatus, and inventors began to concentrate on materials that might enhance thermal insulation. There are several different types of diving suits available today. Passive diving suits, such as wetsuits, dry suits, semi-dry suits, and dive skins, only offer thermal insulation and reduce heat loss by delaying the body's heat transfer into the water [22]. Active diving suits, on the other hand, allow the use of electric heating mechanisms or the provision of warm water [23].

1. Wetsuit

The contemporary wetsuit was created in 1952 by Hugh Bradner, a physicist from the University of California, Berkeley [24]. The wetsuit is clothing worn by those engaging in aquatic activities. It is composed of a highly insulated material, typically foamed neoprene, which is laminated by a fabric. The wetsuit is flexible, so it can stretch enough to be worn, but as soon as divers put it on, it becomes tight around the body. Thus, it allows just a thin layer of water between the diver's body and the inside of the wetsuit. The body can quickly warm the confined thin layer of water, and the foamed neoprene insulates it from the surrounding sea's temperature. Divers select the right wetsuit thickness based on the water temperature. Since hypothermia can occur after prolonged dives even in warm waters, divers wear thin wetsuits under certain conditions.

2. Dry Suit and Semi Dry Suit

Dry suits are composed of waterproof fabrics, and all vulnerable areas, including wrist, neck, and zip joints, are sealed to keep the interior dry and offer superior thermal protection. An intake valve can also be used to inflate them using low pressure air for better thermal results [7]. Semi-dry suits contain seals at the wrists and ankles that are intended to reduce the amount of water that may flow through, making them more like wetsuits than dry suits.

3. Active Diving Suits

Wetsuits and dry suits both provide some degree of thermal protection, but as technology advanced, diving suits that actively work to keep the diver warm were created. These controls might be electric heaters or hot water circulation systems. Hot water suits offer superior thermal defense. When the water is frigid or the bottom times are too long, these suits make a great choice if their usage can be logistically supported [7]. Similarly, active heating vests are designed to keep technical divers warm even during cold water dives by heating the upper body, notably the chest and kidneys. The vest is powered by waterproof, sealed rechargeable batteries [25].

D. THE COMPOSITE K-SUIT

The many varieties of diving suits that are currently available can be used to protect the diver from a range of problems, but mostly against the risk of hypothermia. The sort of suit the diver wears is determined by the ocean's temperature, but if the water is warm enough, the wetsuit is the ideal option. Neoprene's primary drawback, however, is that as the diver descends, the insulating layer thins down and loses some of its thermal properties.

The K-Suit innovation in this research tries to extend the wetsuit capabilities by using composite materials attached to a thin neoprene base. In essence, the K-Suit is designed to use composite pieces consisting of hollow microspheres mixed with polymer. Microspheres have the advantage of remaining almost unaffected as the pressure increases, so they do not shrink as the diver descends to greater depths. Thus, the composite pieces keep their thermal insulation and buoyancy properties constant.

Since 2018 students have been researching materials and building various types of K-Suits. Captain John Brown, in his thesis, while trying to determine the ideal percentage of microspheres, experimented with volumetric microsphere percentage [22]. Lieutenants Aaron Demers and Shane Martin built the first molds for casting composite pieces, and they finally made the "K-Suit Mk.1" [23]. Martin stressed that further testing with a completed wetsuit would need to be done, despite the fact that his most recent studies yielded optimistic findings [26]. Ensign Andrew Kwong-Wright worked alongside Ensign Jared Young to build the second generation of K-Suit Mk.2 in which pieces of composite material were also attached to the forearms, feet, and upper arms [27]. Additionally, Young's thesis was centered on the K-Suit's capabilities as a soundproofing material, along with potential ceramic attachments [15]. Finally, Ensign Andrew Waldron built the last generation K-Suit, the K-Suit Mk.3, in which he used a different method for producing the composite material [28].

E. THESIS DIRECTION

In this thesis the author builds a new generation of K-Suit. The K-Suit Mk.4 includes two layers of composite materials on a 3mm neoprene wetsuit base. The first composite layer consists of 8mm thick glass microspheres mixed with a polymer, as is typical, and the second layer is thinner and made of solid ceramic beads combined with the same polymer. Chapter II examines the benefits and drawbacks of each type of diving suit and presents an optimum diving suit solution for use by Naval Special Operations. The K-Suit Mk.4 might be the safest alternative since it promises to provide divers a better experience by maintaining the ergonomics of the thin wetsuit while including increased thermal insulation, stable buoyancy, and perhaps higher sound protection. Chapter III analyzes the whole composite K-Suit Mk.4 building process, while experimental dives are conducted when the diving suit is finished. Those dives are analyzed in Chapter IV. Data from deeper dives is preferred since it emphasizes the non-compression effect and allows a fair comparison with data from a 7mm diving wetsuit. Finally, this thesis draws a conclusion about whether the K-Suit Mk.4 in its current form has the potential to help Naval Special Warfare Operators or whether the suit requires further modifications.

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II. NAVAL SPECIAL WARFARE OPERATIONS

Divers engage in a variety of underwater activities and select particular equipment based on the purpose of their dive. Some of those activities are less demanding and others very complicated, which means that having the appropriate equipment is essential. Naval Special Warfare Operators such as Frogmen and Explosive Ordnance Disposal (EOD) operators are included in this.

A. HISTORY OF UNDERWATER SPECIAL OPERATIONS

In the previous chapter it was mentioned that diving activities, like acquiring food and searching for treasure dated back to 5,000 BCE. Similarly, the first military diving activities were recorded in Ancient Greek civilization.

Literature claims that the "inventor of undersea warfare" was Scyllias from Skioni, a city in the Ancient Greek Kingdom of Macedonia [29]. Scyllias and his daughter Hydna (also known as Cyana) were ancient Greek swimmers who received recognition for their role in the destruction of the Persian Navy in 480 BCE, as depicted in Figure 7. With the intention of using him against the Greek Fleet, Scyllias was captured by the Persians who knew of his great performance and abilities. According to Herodotus, Scyllias learned of their plans and dove into the sea, cut the ropes from the anchors of the Persian Ships thus creating a great commotion in the Persian Fleet [30]. After that, he managed to slip away and swim for nine nautical miles (9 nm) while emerging from the water and diving in order to reach Artemisio and warn the Greeks about Xerxes' plans [6].

Moreover, during the Athenian campaign to Sicily (415–413 BCE), divers from Syracuse set piles beneath the water's surface to harm Athenian fleet ships, but according to Thucydides, the Athenians dealt with that issue by deploying divers to saw the piles [6]. More underwater demolition teams participated during the Siege of Tyre, in what is now Lebanon, by Alexander the Great (332 BCE). The city's harbor was cleared of obstructions by divers sent down by the invading ship [7]. The Tyrians then attempted to cut the anchor cables, but Alexander countered by putting chains in their place [7].

Figure 7. Scyllias and his Daughter Hydna Undermining Persian Ships.
Source: [31].

Operations for underwater demolition did not greatly advance until the start of World War II. Due to the dominance of both maritime and coastal based theaters of combat during that war, sea-based tactical units such as demolition squads, divers, raiders, scouts, and other aquatic companies expanded. Midway through August 1942, the U.S. Navy and Army started conducting combined training at Amphibious Training Base, Little Creek, Virginia, in response to the growing demand for these kinds of men and teams [32]. The first unit, commissioned in October 1942, participated in operation "Torch," the first allied invasion in Europe, on the North African coast, in November 1942 [32]. Phil H. Bucklew, the "Father of Naval Special Warfare," who is depicted in Figure 8 (left), served in this unit [33]. Landings in Sicily, Salerno, Anzio, Normandy, and southern France were also backed by Navy Raiders and Scouts [32].

Though initially trained for coastal assault, the squads' responsibilities soon expanded to encompass sabotage, recon, and infiltration. More daring U.S. organizations followed, including the Navy Underwater Demolition Teams (UDT) as depicted in Figure 8 (right), Office of Strategic Services Operational Swimmers, and Motor Torpedo Boat Squadrons. Those teams were instrumental in helping the Allies win both the Korean War and World War II.

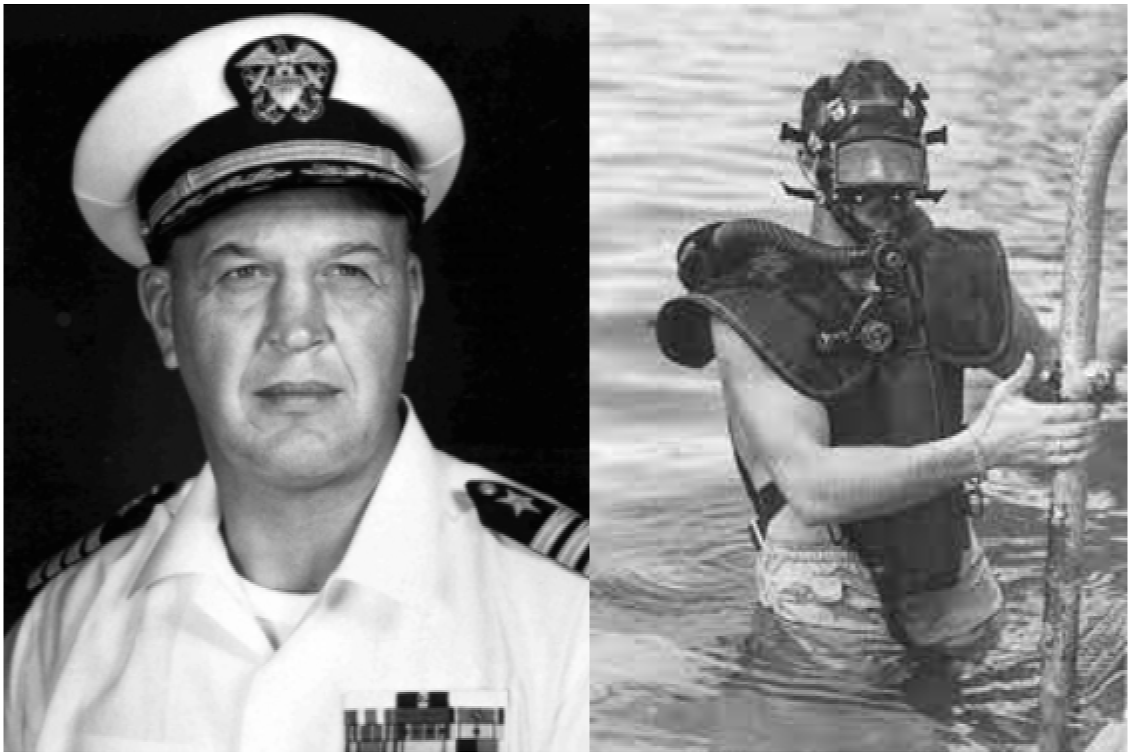

Figure 8. Captain Phil H. Bucklew, the "Father of Naval Special Warfare" (left). Source: [33]. UDT Frogman Diving with a Lambertsen Amphibious Respiratory Unit (LARU) (right). Source: [7].

During 1950s, the U.S. Navy realized that the UDT's role had expanded to encompass a range of "unconventional warfare" [32]. In this sense, the new, more expansive objective ran counter to the UDT's long-standing emphasis on swimming and underwater activities. Capitalizing on the UDT's elite characteristics and waterborne competence while also incorporating ground warfare skills, such as parachute training and counterinsurgency / guerrilla warfare operations, a new type of unit known as the U.S. Navy SEALs, an abbreviation for Sea, Air, and Land, was created [32]. The unit officially came into being after the inauguration of President John F. Kennedy, who backed the employment of special operations forces against guerrilla activities and acknowledged the need for unconventional warfare. In order to create its new special operations force, the U.S. Navy proceeded ahead and commissioned SEAL Teams ONE and TWO in January 1962 at NAB Coronado and NAB Little Creek, respectively [32].

B. CONTEMPORARY NAVAL SPECIAL WARFARE

The development of the U.S. Navy Seals added a new dimension to Underwater Special Forces and laid the groundwork for creating analogous units throughout the world. Contemporary Naval Special Warfare contains a broad field of Special Operations in all kinds of fields; however, the underwater part may be combined as part of unpredictable infiltration or main action.

1. Navy EOD Technicians

Mines and unexploded devices endanger the waters in which Special Operations and conventional forces may operate. Explosive Ordnance Disposal professionals choose techniques and methods for finding and neutralizing all kinds of explosive ordnance and granting access to restricted places, as shown in Figure 9.

EOD divers use rebreathers with mixed air that allows them to dive in waters as deep as 300 FSW. They carry tools and explosives for doing their work, but all their action takes place at the spot where the ordnance is located. Therefore, depending on the mission, they can utilize thick diving suits to withstand the prolonged dives in frigid waters, partially sacrificing maneuverability.

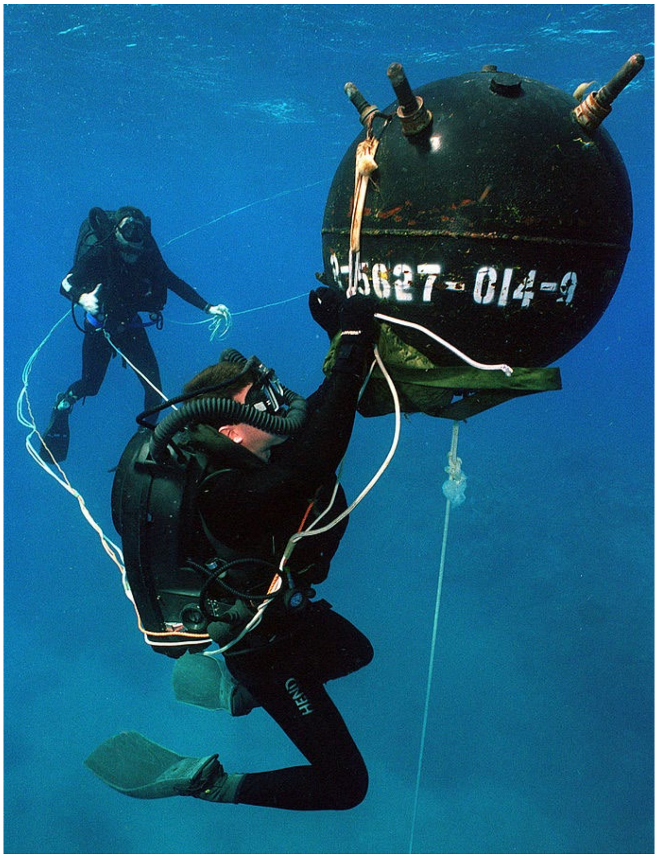

Figure 9. Navy EOD Neutralizes an Underwater Mine. Source: [34].

2. Navy SEALs' Underwater Infiltration

Navy SEALs may use underwater penetration to exit a coastal area and continue their mission ashore or even be tasked with striking a target of opportunity, such as placing limpet mines on warships or explosives on bridge piers crossing water obstacles.

To reach the precise location where their dive action begins, operators may use a variety of methods, including helicopter drops, military free falls from airborne platforms, fast crafts, inflatable boats, or even submarines as shown in Figure 10. Frogmen select their equipment in accordance with each distinct mission due to the intricacy, combination, and variety of means and targets.

For instance, if the objective is to attach underwater explosives to a target ship's hull, operators may employ a submarine for area insertion and brief diving for infiltration at the very end. Frogmen are permitted to carry less gear and more explosives, and in this case, the proper diving suit may be more thermally insulating than maneuverable.

Things get more challenging in another case as operatives must sneak through a rugged coastal region before continuing their operation inland. Thus, more weapons, communication devices, and specialized equipment must be used by frogmen. In this scenario, divers would choose a less cumbersome and more nimble diving suit.

Figure 10. NSW Diver Exiting from a Submarine. Source: [35].

3. Seals Delivery Vehicle

The SEAL Delivery Vehicle (SDV) is a type of swimmer delivery vehicle and manned submersible used to transport U.S. Navy SEALs and their gear for special operations missions. Since 1983, SDVs have been in operation continuously and are primarily employed for covert or clandestine missions into restricted regions.

SDVs offer frogmen improved deployment capabilities. With a dive crew of six SEALs, the pilot, the co-pilot, and four warriors, the Mark 8 Mod 1 SDV which is shown in Figure 11, has a range of 15 to 18 nm and an endurance of eight to 12 hours [36]. The operational depth depends on the divers' limits, and they could stay for more than three hours, riding the SDV in cold waters before they start moving to reach the target or the exiting point ashore.

This method requires the selection of diving suits that offer increased thermal protection, along with agility. Dry suits are not appropriate in this situation since they do not provide improved ergonomics and they run the risk of tearing as divers approach rocky beaches.

Figure 11. Navy SEALs Infiltrating with a SDV Mk VIII Mod 1. Source: [37].

C. FUTURE UNDERWATER OPERATIONS

Navy Special Warfare operatives will constantly be busy thanks to the limitless coasts that are available for infiltration and the capability to strike targets of opportunity.

1. Unmanned Vehicles

Underwater Unmanned Vehicles (UUV) can be used as offensive weapons since they can be operated remotely and in contaminated or freezing waters without exposing underwater demolition teams. However, UUVs are mostly specialized in one domain and cannot provide the ultimate solution or replace frogmen. For instance, underwater diving infiltration might be just the first stage of an operation that will be continued inland.

2. Sonars as Counter-Diver Measures

There is a variety of means and equipment to deter swimmers and divers from a restricted area. A safe barrier net that is coupled to a system for site-wide alerts can offer a number of detecting zones. Moreover, a bypass loop may be used to alert authorities if a breacher tried to cut the net covertly. The U.S. Navy uses the MK6 Marine Mammal System to locate objects in the surrounding water, such as divers and swimmers as well as mines, by utilizing dolphins' innate sonar. This system, which has been used on several occasions, was deployed to Vietnam in 1970–1971 and the Persian Gulf in 1987–1988 to detect and locate intruders [38]. However, the cost of protecting endless coast lines is prohibitive and states may be able to afford to protect only vital areas, such as harbors.

According to University of Texas research, the only technology that can cover a broad harbor area at an affordable price is acoustic sound generators that produce high intensity, extremely low frequency noises [38]. The previous chapter introduced the idea that neoprene wetsuits offer a degree of sound protection to divers. However, wetsuits with a layer of material denser than water may be able to reflect the sound wave and protect the diver better, just as wearing a helmet protects more than donning a neoprene hood [7].

3. Great Power Competition

Following the 2018 *National Defense Strategy*, the U.S. Department of Defense shifted its emphasis from counterterrorism (CT) and external internal defense (FID) operations, which were more focused on special forces, to what is now known as the "Great Power Competition (GPC)." Some analysts believe that the large branches are best suited to deal with the GPC and emphasis should be placed on the development of conventional forces while special forces move to a supporting role [39]. The bulk of special operators work with and train partner forces all over the world; therefore, according to some experts, Special Forces engage in daily rivalry with GPC enemies by denying them influence and depriving them of prospective partners [40]. Additionally, they think that adversaries prefer to operate in the grey zone area where Special Forces are more effective.

4. Arctic Region

Environmental changes gave rise to opportunities for the exploitation of the Arctic area, including the utilization of its natural resources and the control of its polar sea routes. Unprecedented claims and militarization of the Polar waters by the Great Powers leads to significant focus on the Arctic region [41]. Due to the difficult terrain, Special Forces begin concentrating in the Arctic and honing their survival techniques on the arctic battlefield [42]. The next step in this process is to look for new, innovative ways to make more suitable equipment, and a diving suit with improved thermal capabilities without sacrificing other qualities would be essential.

D. A WICKED PROBLEM AND THE OPTIMAL SOLUTION

In defining the problem that Naval Special Warfare Operators face, it is accurate to say that they must dive into cold waters for a prolonged time to infiltrate in demanding environments. Therefore, a diving suit built from a material that has thermal resistivity is the solution. But during the process of building a technologically advanced suit, the author realized that there is more than one solution to our problem, unlike providing an answer to a math equation. Tradeoffs exist for every single material solution that people want to buy. And even if a designed material covers all the technical aspects of the defined problem ideally, this material is likely to be too expensive. So, solutions are and might be good or bad, but not true or false.

Looking at the diver's problem, it is easy to build a very warm wetsuit, but it will be very thick. In this case, the well-defined problem of building a warm diving suit becomes more complex, because the suit becomes less ergonomic and positively buoyant. In other words, in fixing the specified problem, other problems are created, and sometimes there is no way to avoid these interrelated sub-problems.

Another aspect of making products, while having to choose between trade-offs, is that each person may want to give specific gravity to each factor (thermal protection, ergonomic, buoyancy) and make an ideal diving suit for the client. When it comes to commercial production, where designers must build a product and sell it to a large community and make a profit, designers must categorize every individual's desire and develop an optimal solution, covering most of the demands in such a way that the cost will remain low.

Given that it is not feasible to provide the ideal solution for designing a diving suit that covers all the needs of Navy Special Warfare Operators, the author feels that the K-Suit Mk.4 will be the nearly optimal solution, meeting the most crucial demands of underwater operations.

III. BUILDING THE PROTOTYPE WETSUIT

The K-Suit Mk.4 took a long time to develop. Local company Otter Bay Wetsuits built the core neoprene wetsuit in approximately two months, and it took one additional month to attach the pockets with the composite parts. The construction of such composite parts in the lab took around 80 hours.

A. NEOPRENE CORE WETSUIT

Neoprene is the most popular material used worldwide to make wetsuits, as briefly covered in earlier chapters. Since the 3mm neoprene wetsuit that serves as the basis of the K-Suit directly influences how the composite material will be patched onto this base, this section examines neoprene’s properties and the construction of our core wetsuit.

1. Neoprene History and Characteristics

Natural rubber costs rose steadily during the 1920s due to rising demand, which led to research for an equivalent synthetic rubber. Neoprene was developed in 1930 by Wallace Carothers, a scientist working for DuPont’s basic research division, and became ideal for various industrial insulation uses [43].

Neoprene’s core material is polychloroprene, which is produced by the polymerization of a colorless liquid, the chloroprene (CH2=CCl-CH=CH2) [44]. Chips of polychloroprene are melted, combined with foaming agents and carbon colors, and finally baked to cause expansion [44]. The finished product is then cut into smooth neoprene sheets of various thicknesses, as depicted in Figure 12 (left) [44]. The thin-edged layers of neoprene sheets have advanced sealing features and are separated from the core of thicker neoprene material for use at the edges of the sleeves on semi-dry and dry suits.

Neoprene became the most popular material for wetsuits in the early 1950s in California. Hugh Bradner, an American physicist at UC Berkeley, devised the wetsuit as a result of his love of diving and the needs of the Navy Frogmen [45]. However, the wetsuit industry was started by surfers in Northern California, a former Navy pilot Jack O’Neill, who subsequently formed the now-famous O’Neill brand, and the Meistrell Brothers who invented the Body Glove brand [46].

Neoprene was a difficult material to put on, tore easily, and was fragile at the time. This issue was remedied in the 1960s by laminating cloth over neoprene as shown in Figures 12 (right) and 13, which produced the contemporary wetsuit. Foamed neoprene can be produced with either an open-cell or a closed-cell structure [34], while the gas bubbles can be made from nitrogen (0.024 W/(m K)) or argon, which has the least thermal conductivity (0.016 W/(m K)) [47]. At this point it is important to note that spearfishermen frequently utilize the so-called “open-cell” wetsuit, which does not correspond to the way foamed neoprene is constructed. These wetsuits are only laminated from the exterior side of the material, while the interior of the neoprene is shaved to have a tighter touch with the body of the spearfisherman. This method helps to create a thinner barrier of water between the skin and the wetsuit, which improves thermal insulation and maneuverability while sacrificing durability.

Figure 12. Manufacturing Neoprene Sheets (left). Source: [48]. 1mm Thickness Neoprene Sheet with Double Sided Lamination (right). Source: [49].

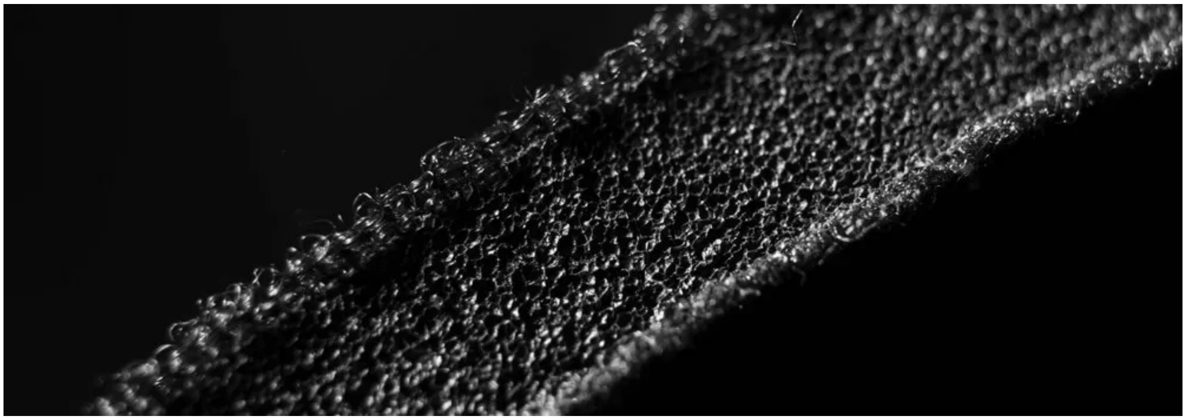

Figure 13. Neoprene Laminated with Nylon Cloth on Each Side. Source: [48].

Neoprene still remains the main material for wetsuits due to its characteristics: light in weight, impermeable to water, durable for twisting, flexible for stretching, able to maintain its characteristics over a wide temperature range, and thermally insulative [50]. However, it has one major weakness for underwater use. The volume of the gas bubble decreases as the ambient pressure increases, which results in reduced thermal insulation. For example, the ambient pressure at the surface is 1 atm, but at a depth of 33 feet, the pressure is double that, causing the gas volume to fall by a factor of two.

2. Building the Neoprene Core Wetsuit

Since the composite material has inferior flexibility compared to neoprene, we built a thin 3mm neoprene wetsuit as the core, where we attached the composite material into pockets. The core custom-fitted wetsuit was built by Ruth Justice-Limes, owner of the local company Otter Bay Wetsuits. First, she measured my body's dimensions for ideal fitting results. Then she tailored neoprene pieces cut from a 3mm neoprene sheet made by Glomex [51]. For our wetsuit, Otter Bay Wetsuits used a sheet of 32 square feet, while some pieces of that sheet remained unused.

The tailored pieces were glued two times on their edges and then attached together to form the basic wetsuit parts (legs, arms, chest, back). Subsequently, a large zipper was sewn in the middle of the back part in order toto provide the ability to get in and out of the suit. Finally, after gluing all the parts, Ms. Justice-Limes sewed and then glued those parts to enhance the wetsuit’s durability. The sewing procedure essentially connects the two nylon clothes on the interior side and the two others on the exterior.

I donned the wetsuit when it was finished, and we found that it needed some tweaks to fit better. Ms. Justice-Limes measured two parts that had to be smaller in the knees and the abdomen; she cut small pieces from those parts, and then she glued and sewed the new edges. After the second in-store fitting, we decided to proceed with adding the composite materials to the core wetsuit.

3. Takeaways from Neoprene Wetsuit Building

The only places where water may enter to generate the thin water barrier between the body and the suit are the stitched portions, the zippers, and the edges of the wetsuit (neck, arms, legs) since solid neoprene components are impermeable to water. In the market there are waterproof zippers which are usually used for dry suits, but their cost makes their use cost prohibitive.

The design of the Mk. 4 suit covered larger area of the arms and legs than previous versions of K-Suit, which ended up making the suit difficult to wear. Adding more zippers to the legs and sleeves was considered, then discarded because it could increase the amount of water allowed into the suit, sacrificing warmth for wearability. Perhaps the best solution for the next K-Suits is to be less aggressive regarding the coverage area at the edges of the leg and lower arm parts. Otter Bay Wetsuits minimized the water coming in from the stitched portions by adding glue over the stitched parts.

The most important proposal for future neoprene wetsuits is to try the wetsuit in the water before proceeding with the attachment of composite materials. The reason for this is that any small leakage cannot be detected when somebody wears the wetsuit outside the water. Any leakage that will be noticed later will lead to a connection of neoprene parts only by gluing them since the bulky parts of the K-Suit will not allow them to be sewn. This is exactly what happened when I discovered that I needed to reduce some of the bulk in the upper legs and neck of my suit.

B. COMPOSITE MATERIAL SELECTION

In his thesis, Brown researched insulated and incompressible glass microspheres and experimented with volumetric microsphere percentage to determine the ideal mixing percentage with polymer [22]. The K1 glass microspheres from 3M were designed with an intended fractional survival of 90% and an isostatic crush strength of 250 psi (8250 FSW) [52]. Their typical true density is 0.125 g/cc, and they have the optimal thermal conductivity (0.047 W/(m*k) at 70°F), compared to the rest of the K and S series of 3M glass microspheres.

The main purpose of designing the K-Suit Mk.4 was to build an advanced thermally insulated and neutral constant buoyancy wetsuit. In the initial phases of research, other materials were considered to account for potential anti-ballistic or underwater sound protection. Following Brown's method, I compared specific heats of potential materials. I focused on a heavier material than glass that could be combined with hollow microspheres or used alone. Ceramics were the main direction since their thermal conductivity varies (from 1.5 to 150), and there are types of ceramics that have the smaller thermal conductivity compared to other solid materials, as we can see in Figure 14 [53].

A promising insulating material was the HY-TECH ceramic hollow microspheres, depicted in Figure 15. They have a softening point of 1800° C, a compression strength of up to 6,000 psi, and a low thermal conductivity of 0.1 W/(m*K) [54]. However, using simply ceramic hollow microspheres would be less effective thermally than using glass hollow microspheres.

Finally, I decided to use a layer of 8mm hollow galls microspheres as the previous students did, combined with a thinner 4mm layer of solid 3M ceramic microspheres W610 with 2.3 (W/mK) thermal conductivity [55]. In doing so, I aimed to establish a neutral constant buoyancy while simultaneously increasing the thermal resistance of the K-Suit. Additionally, other specifications like acoustic protection might also benefit.

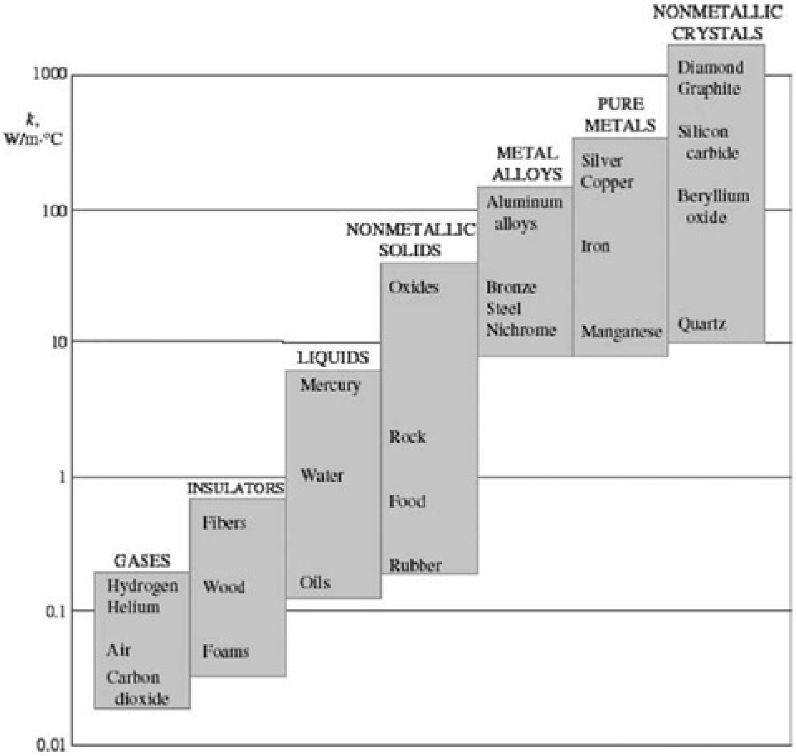

Figure 14. Spectrum of Materials' Thermal Conductivity at Room Temperature. Source: [56].

Figure 15. HY-TECH Ceramic Hollow Microspheres. Source: [54].

C. COMPOSITE MATERIAL CASTING

To cast pieces of composite material, I needed molds in which I could purify the mixture. Thanks to former NPS students, molds for the glass microspheres had already been made for almost the whole human body. For the prototype wetsuit Martin and Demers captured Martin's body 3D scans and converted the raw imaging into files available for 3D printing [26]. They made molds for the chest, back, thighs, and abdomen pieces as shown in Figure 16. The remaining elements of the human body, including the forearms, shoulders, and shins, were later created by Wright utilizing Martin's scans [27]. The composite molds for glass microspheres were designed to produce 8mm thick pieces.

Because I needed a layer that was roughly 4mm thinner, I did not utilize the same molds to cast the composite layer of ceramic microspheres. Furthermore, because the ceramic layer was more flexible, I could create small sheets of ceramic layers without the requirement for molds designed specifically for human bodies.

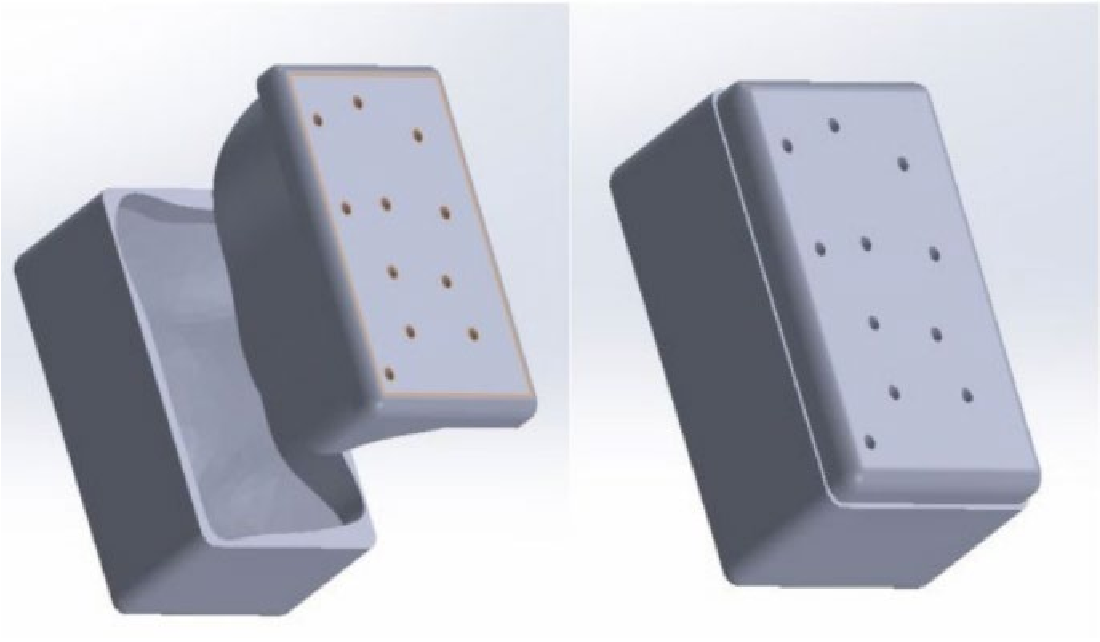

Figure 16. For the Casting Process, 3D Body Scans Translated into Two-Piece Molds. Source: [15].

1. Glass Microspheres Composite Layer

The construction of the composite parts made from glass microspheres involves eight stages: mixing the components, spinning the mixture, degassing, pouring the mixture into the molds, curing the finished product, removing it from the mold, cleaning the mold, and lastly, fining the final product.

Polydimethylsiloxane (PDMS) silicone elastomer base and curing agent from Dow Corning Corporation Sylgard 184 were mixed in a 10:1 ratio to generate the silicone prepolymer for the wetsuit panels. Using a 310 mL mixing cup, I combined roughly 10 g of the curing agent and 100 g of the elastomer base as depicted in Figure 17. Subsequently approximately 150 mL, or equivalently 10 g, of 3M K1 hollow glass microspheres were added in the mixture. The components were weighed on a highly accurate weight scale, and the precise quantity of each combination is shown in Appendix A.

Figure 17. Mixing the PDMS Elastomer Base with the Curing Agent in a 310 mL Mixing Cup, on a Highly precise weight scale.

The mixing cup was sealed with enough empty room allowing for proper mixing, then spun for four minutes at 1500 rpm in an ARE-310 THINKY rotary mixer as depicted in Figure 18. Before starting the mixer, a counterweight inside was also set to counteract the centrifugal force of the cup. The rotary mixer retains the cup at an angle, allowing material to flow in three dimensions while protecting the microspheres, exploiting the absence of mixing blades.

Figure 18. Cup with Composite Mixture in a THINKY Rotary Mixer Preset for Four Minutes Spinning at 1500 rpm. Source: [15].

The uniformly mixed slurry was added to a desiccator that was connected to a mechanical vacuum pump. For 15 minutes, up to five cups of mixture were simultaneously degassed as shown in Figure 19 (left). For effective degassing, the vacuum distillation technique requires the use of a powerful vacuum pump and tightly sealed desiccator. However, such a strong pumping increases the mixture to the point where overflow is possible. Therefore, caution must be used while shutting off the vacuum pump and waiting for a minute to allow the mixture to rest and then turn it again on.

Waldron applied a different method for degassing. As shown in Figure 19 (right), he poured the mixture from the cups to a bigger Pyrex bowl and then degassed it [28]. This results in a more efficient degassing method, but we lose part of the mixture that, due to its viscosity, remains in the cups and some other quantity that remains in the Pyrex. Moreover, it is easier to calculate the exact amount of the mixture needed when pouring directly from the cups into the molds.

The ideal solution would be to pour the mixture from the cups into the molds and then degas the mixture by putting the mold in a larger desiccator. This is because even if the substance is perfectly degassed, extra bubbles will still be produced since air is trapped when the viscous mixture is poured into the mold.

Figure 19. Degassing Three Cups with Mixture in a Desiccator Connected to a Mechanical Vacuum Pump (left). Pouring Glass Microspheres Mixture from a Cup to a Pyrex Bowl (right). Source: [28].

During the pouring process, the mixture is concentrated in the lowest spot of the mold; as a result, the lid must be pressed down firmly to spread the mixture equally. Thus, it might be difficult to know the exact amount to pour. If the mixture is just right or slightly too much, not much power is needed to close the lid entirely, and the excess will run through the holes in the lid. If there is less than what is needed, the lid will close quite quickly, but the item will not be finished, and the cast will need to be repeated. Another issue is that if there is too much mixture, the lid will be difficult to fully seal, which might result in a piece with a remarkably different thickness, and it will also be challenging to remove the lid after the curing process. The issue gets worse for molds with side walls that are perpendicular to the mold's bottom, and the mixture is not supposed to get between those walls and the lid, as shown in Figure 20. A table with the roughly proper number of cups for each mold has been provided in Appendix A to make future usage of the same molds convenient.

Figure 20. Molds Filled with Considerably more Mixture than Necessary.

Since the typical material cure period is 24 hours at room temperature, the molds were put in a VWR Forced Air Oven for two hours at 80° C. Afterwards, the molds were taken out of the oven and allowed to cool to room temperature. It is crucial to note that occasionally using great force to remove the lid from the mold might result in the lid breaking. The more effective method is to attempt to shove four long screwdrivers under the lid at once, one from each corner, as shown in Figure 21 (left). Future molds can be made with diagonal walls to use less power for removing the lid. To prepare the molds for the subsequent iteration, the cast was detached, and excessive debris was cleaned out of them with the help of a drill, as depicted in Figure 21 (right). Finally, on the cast itself, any extra material and agitated corners were removed, rounded with a blade, and discarded. Figure 22 shows nine of the 19 total glass microspheres composite pieces.

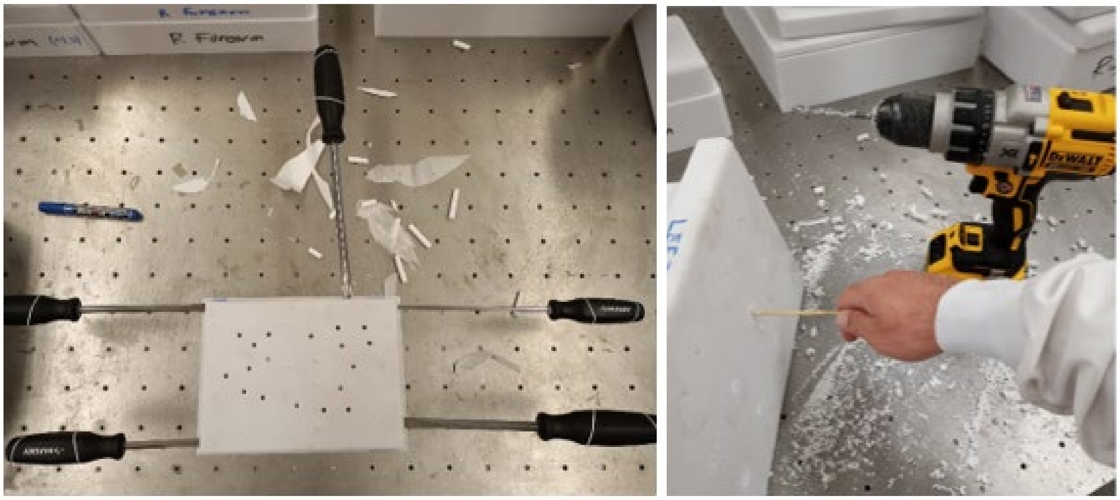

Figure 21. Removing the Lid from the Mold with the Use of Screwdrivers (left). Cleaning Excessive Debris from the Mold with the Use of a Drill and a Wooden Stick (right).

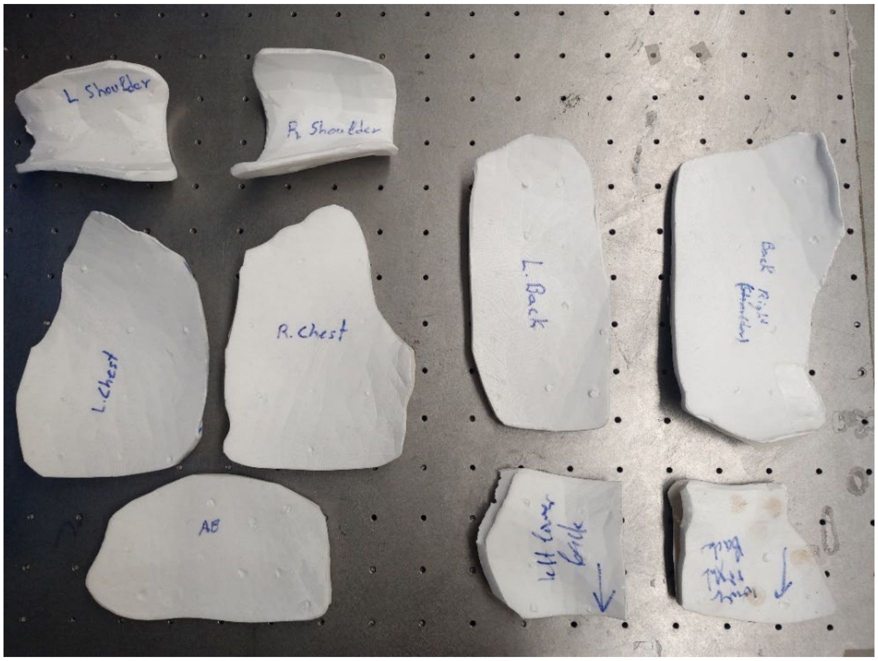

Figure 22. Finished Glass Microspheres Pieces.

2. Ceramic Microspheres Composite Layer

Except for using pans rather than molds, the procedure for building composite components manufactured from ceramic microspheres was similar to the one used for glass microspheres.

The same ratio of silicone elastomer base and curing agent were mixed with the approximate amount of 150 mL, or equivalently 120g, of solid 3M ceramic microspheres W610. The components again were weighed on a highly accurate weight scale, and the precise quantity of each combination is shown in Appendix A.

Because this solution was heavier than the previous one and did not greatly expand, it was not necessary to turn the pump off to let the solution rest. As a result, the experimental degassing procedure went more quickly and easily. Then, as seen in Figure 23, we poured the mixture into a flat pan and baked it.

Figure 23. Ceramic Microspheres Mixture Poured in a Pan.

The next step was to draw the periphery of the glass microsphere casts on the ceramic composite layer, as shown in Figure 24, and then cut the pieces with a razor. Additionally, to estimate the size of the human body covered by each piece, we drew squares measuring 3 cm by 3 cm. Appendix B displays each cast component area.

Figure 24. Ceramic Microspheres Cast where the Periphery of Two Glass Microsphere Pieces Are Drawn.

After the fining of the ceramic microspheres casts, the next step is to glue one of them to its respective glass piece. In order to get the optimum bonding outcomes, Gorilla white glue is used and the pieces are clamped together for 12 hours, as shown in Figure 25 (left), whereas Figure 25 (right) shows a finished composite piece with both the ceramic and glass layers bonded.

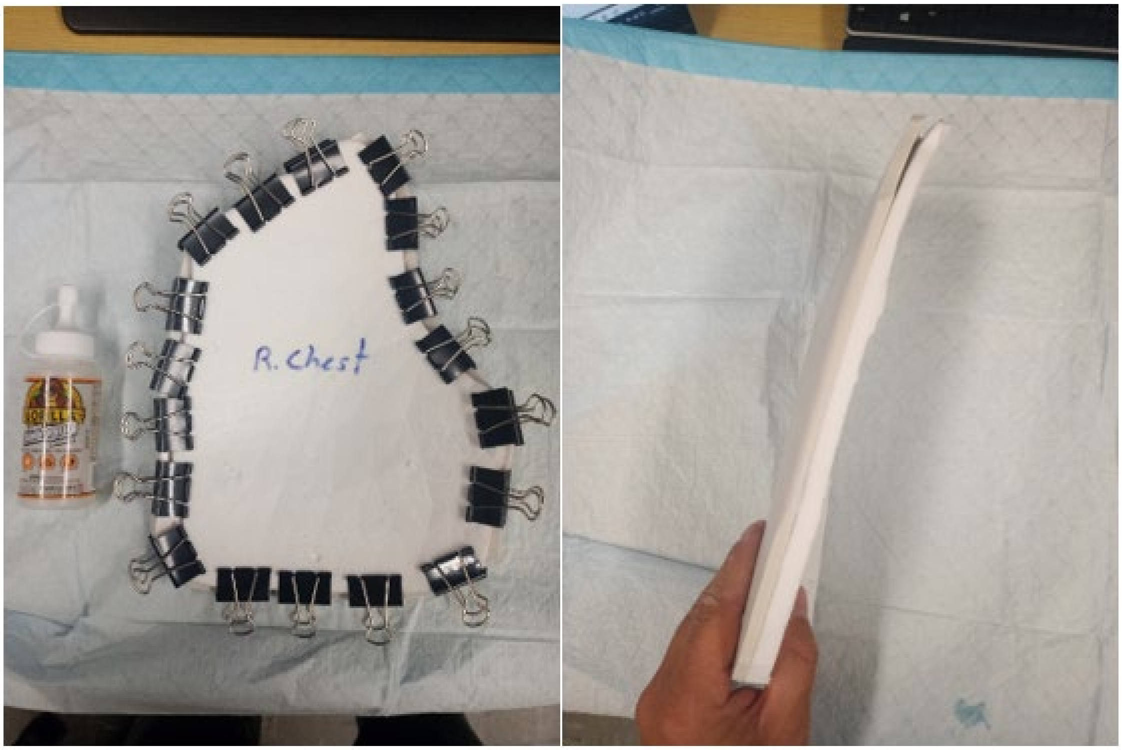

Figure 25. Gluing a Glass Cast with a Ceramic Cast (left). Finalized Composite Piece (right).

3. Testing Buoyancy

Since the composite material's optimal buoyancy should be neutral or slightly positive, its buoyancy is evaluated in a bowl of unsalted water. The outcomes were satisfactory and roughly in line with what was anticipated when determining the ceramic layer's thickness. Each composite buoyancy is depicted in Appendix B.

D. FINALIZING THE K-SUIT MK.4

Since the neoprene core wetsuit and the composite pieces were ready, the last step was to create neoprene pockets for the composite pieces. When I put on the wetsuit, Ms. Justice-Limes indicated how the composite sections should fit. She then cut out pockets from 2mm pieces of neoprene and attached them to the wetsuit. Since stitching was not an option due to the thickness and rigidity of the composite components, the pocket process was the only way to keep the composite pieces in place and water out of the suit. Since it is very hard to make modifications once the pockets are bonded, their measurements should all be exact. After the first three dives, we recognized that the neck's zipper, the sleeves, and the abdominal and hip areas needed to be modified. Figure 26 shows the completed K-Suit Mk.4 prototype.

Figure 26. Completed K-Suit mk.4 Prototype.

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IV. EXPERIMENTAL RESULTS

Field experiments were conducted to assess the K-Suit Mk.4's capabilities in further detail. Six dives were accomplished, and data on temperature and pressure between the diver's diving suit and chest were collected and compared to the ambient conditions for each dive.

A. DATA LOGGING DEVICES

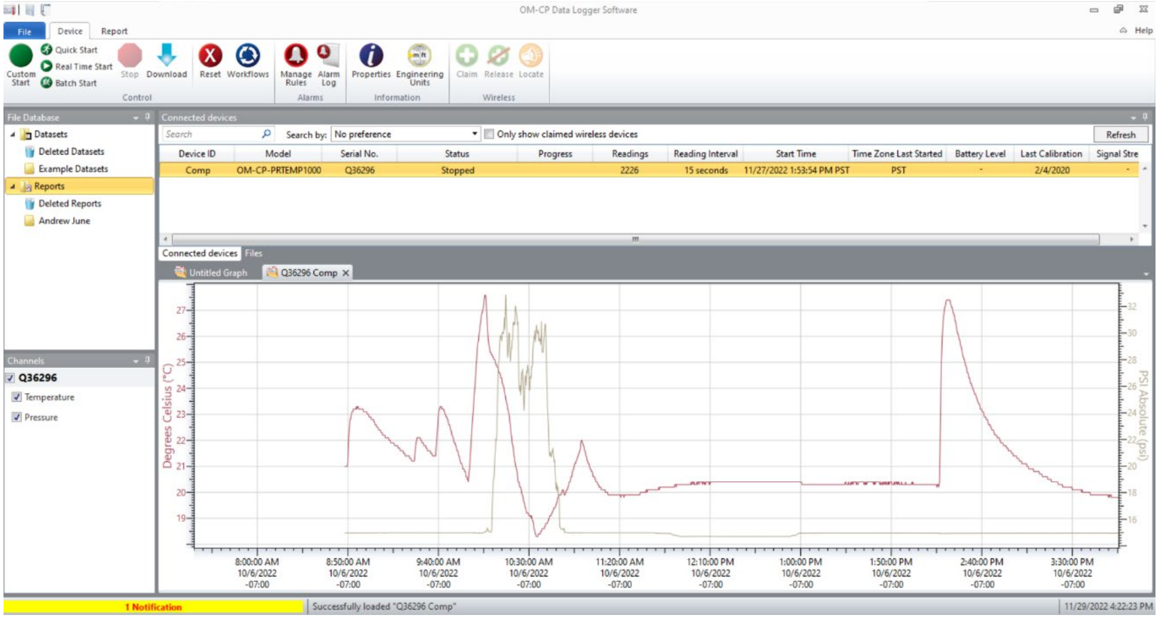
The laboratory offers reliable pressure and temperature data recorders that can be utilized to capture underwater data. The Omega OM-CP-PRTEMP1000 loggers are 1.25 inches diameter cylindrical and 6.5 inches-long stainless-steel devices. These devices are small enough to fit in the space between the diver's chest and diving suit without disturbing their underwater activities.

I used the OM-CP Data Logger Software to turn on the loggers before each dive and to retrieve the data afterward in an Excel format. Figure 27 shows how I connected the data logger to the laptop's USB port using a USB-3.5 jack adapter. The data logger and its serial number appear under the device tab after being plugged into the laptop, as shown in Figure 28. Then, I had the choice of activating the device to begin recording data, turning it off, collecting the data, or even erasing the data. The intervals between measurements can also be adjusted, and I set up the devices to collect readings every 15 seconds.

There are options to start the device immediately or start at a specific time in the future. However, it is safer to delete previous data and enable the device before the dive and make sure that readings increase. It is important to mention that the last calibration was in February / March 2020, but still all the loggers recorded approximately the same pressure under the same conditions and at the same time.

Finally, I also used a Fitindex e-scale to measure the biometrical data of the divers before each dive.

Figure 27. Connecting Data Logger to a USB Port.



Search by: No preference

☐ Only show claimed wireless devices

Device ID	Model	Serial No.	Status	Progress	Readings	Reading Interval	Start Time	Time Zone Last Started	Battery Level	Last Calibration	Signal Stre
Comp	OM-CP-PRTEMP1000	Q36296	Stopped		2226	15 seconds	11/27/2022 1:53:54 PM PST	PST	-	2/4/2020	-

☑ Q36296

☑ Temperature

☑ Pressure

Successfully loaded "Q36296 Comp"

Figure 28. OM-CP Data Logger Software.

B. DIVING EXPERIMENTS

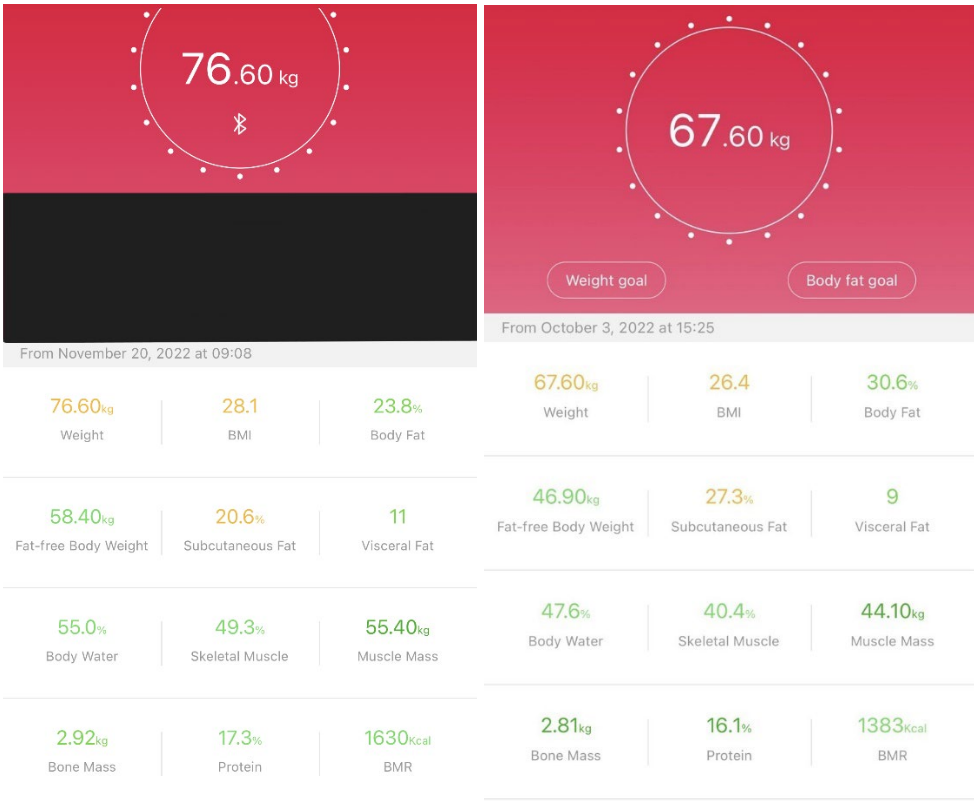
Monterey is very popular as a SCUBA diving destination in Northern California, and people come from all over the Bay area to attend dives. Scheduling deep water dives can be difficult, since the only beach that offers a short descent to 90 feet is Monastery Beach, which is often impacted by a strong swell. It would be beneficial to emphasize that the K-Suit Mk.4 retains its thermal insulation qualities as I was going to compare it to a 7mm diving wetsuit and gather data for more than 15 minutes at a depth of 90 feet. In all, I managed to dive six times, four times in San Carlos Beach, which offers shallow water dives, and two times in deeper waters. Since all the dives took place during October and November, finding a buddy who used a 7mm wetsuit was challenging, and most of my buddies wore a thicker suit or a vest underneath the diving suit.

I used three data recorders and followed the identical process for all of the dives. One device monitored the ambient pressure and temperature, and one was placed between each diver's chest and diving suit. In order to ensure that I would compare the findings under the same ambient environmental conditions, I always sought to remain immediately close to my dive partners and never stayed more than three feet away from them.

1. Dive 1: October 3, 2022—San Carlos Beach Breakwater

Once the K-Suit Mk.4 was complete, it was more appropriate to test it in shallow waters to check for leaks and evaluate its buoyancy. The first dive was successfully completed at San Carlos Beach Breakwater on October 3, 2022. The biometric information of the divers is shown in Figure 29. Diver A, who had a metabolic age of 41, dove with the K-Suit Mk.4, whereas diver B, who had a metabolic age of 38, used an Aqualung 7mm wetsuit with a 2mm vest underneath.

For the first dive I tried to activate the Omega loggers at a certain time rather than using the quick start option. Unfortunately, only the data logger for Diver A was functional. Diver B's data logger failed to activate in a timely manner. Nevertheless, I was able to use the ambient temperature measurements from the dive which were recorded by my Garmin watch.



76.60 kg

From November 20, 2022 at 09:08

76.60kg	28.1	23.8%
Weight	BMI	Body Fat
58.40kg	20.6%	11
Fat-free Body Weight	Subcutaneous Fat	Visceral Fat
55.0%	49.3%	55.40kg
Body Water	Skeletal Muscle	Muscle Mass
2.92kg	17.3%	1630Kcal
Bone Mass	Protein	BMR

67.60 kg

From October 3, 2022 at 15:25

67.60kg	26.4	30.6%
Weight	BMI	Body Fat
46.90kg	27.3%	9
Fat-free Body Weight	Subcutaneous Fat	Visceral Fat
47.6%	40.4%	44.10kg
Body Water	Skeletal Muscle	Muscle Mass
2.81kg	16.1%	1383Kcal
Bone Mass	Protein	BMR

Figure 29. Biometrical Data of Diver A (left) and Diver B (right).

Figure 30 displays depth readings over time as well as the delta temperature between Diver A wearing the K-Suit Mk.4 and the surrounding water. For Dive 1 there was no opportunity to compare the K-Suit Mk.4 with another diving suit; however, we realized that the temperature differed considerably by around 8° C between the maximum and minimum delta temperatures. Moreover, we noticed that when Diver A was ascending or descending there was a significant change in temperature. Comparing the data with the diver's experience, we realized there were leaks from the zipper and probably the sleeves. Furthermore, Diver A realized that there was plenty of water in the abdominal and hip areas, which partially justifies those results. First, it is difficult for the body to warm up a large water layer between the diving suit and the body, and second, the concentrated water moves to other areas when descending or ascending.

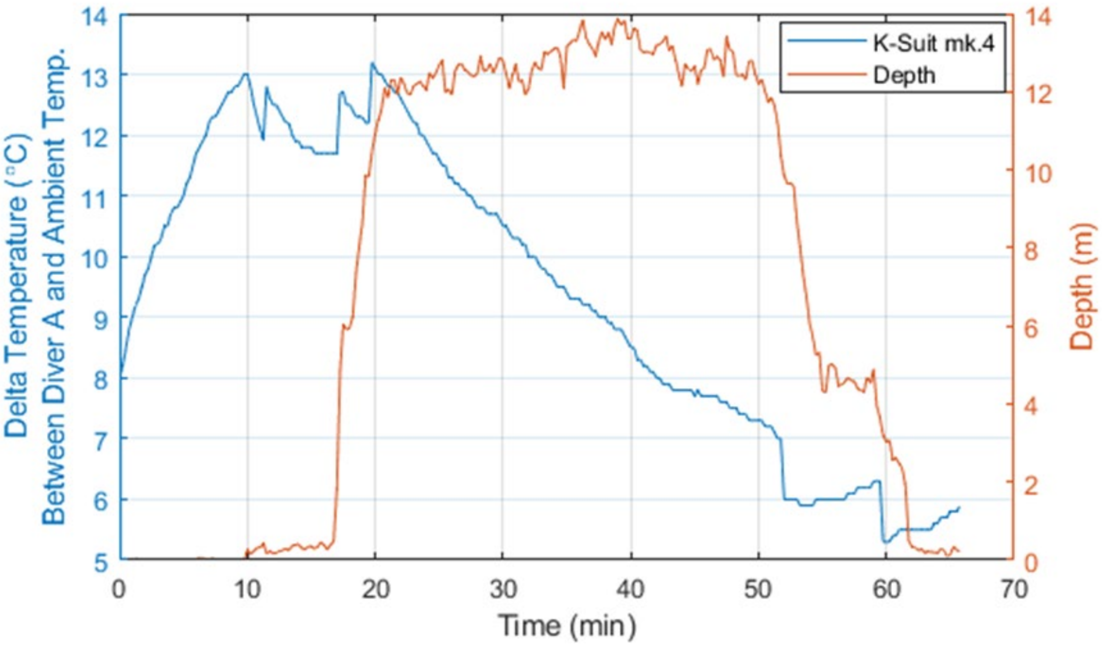


Figure 30. Delta Temperature between Diver A Wearing the K-Suit mk.4 and Ambient Temperature, along with Depth Measurements over Time.

2. Dive 2: October 4, 2022—San Carlos Beach Breakwater

The second dive experiment took place on October 4, 2022, at the same spot, but this time all the loggers worked properly. Diver A, who dove with the K-Suit Mk.4, was the same for all the dives, so we will not represent his biometrical data again. In Figure 31 we can see the biometrical data of Diver C, who has a metabolic age of 32 and was wearing a 7mm BARE ultra-warmth technology wetsuit and a 3mm vest underneath.

Diver A adjusted the sleeves by donning scratched-up gloves to reduce leaks and a hoodie that covered the neck's zipper. Figure 32 shows the difference in temperature between divers and ambient temperature as well as the difference in temperature between Divers A and C over time. It is evident that Diver A's maximum and minimum delta temperature differences have improved by roughly 3° C.

Both divers' temperatures generally follow the same trends, although Diver C is around 5° C warmer than Diver A thanks to his wetsuit's significant advantage in thermal insulation. This benefit is offset by the ergonomic disadvantage of wearing a 7mm wetsuit, though. More specifically, after 15 minutes of dive the delta temperature difference between Divers A and C reaches the lowest point of about -5.5° C; however, this difference improves slightly up to -4.5° C for the rest of the dive.

Since the dive took place in relatively shallow water, it is challenging to identify variations in temperature trends comparable to the depth shrinkage. However, Diver C’s wetsuit, which is 7mm thick and is layered with a 3mm vest, is still sufficiently thick to compensate for the water temperature.

From October 4, 2022 at 17:51

92.75kg Weight	27.4 BMI	21.9% Body Fat
72.50kg Fat-free Body Weight	18.9% Subcutaneous Fat	10 Visceral Fat
56.4% Body Water	50.5% Skeletal Muscle	68.80kg Muscle Mass
3.63kg Bone Mass	17.8% Protein	1934Kcal BMR

Figure 31. Biometrical Data of Diver C.

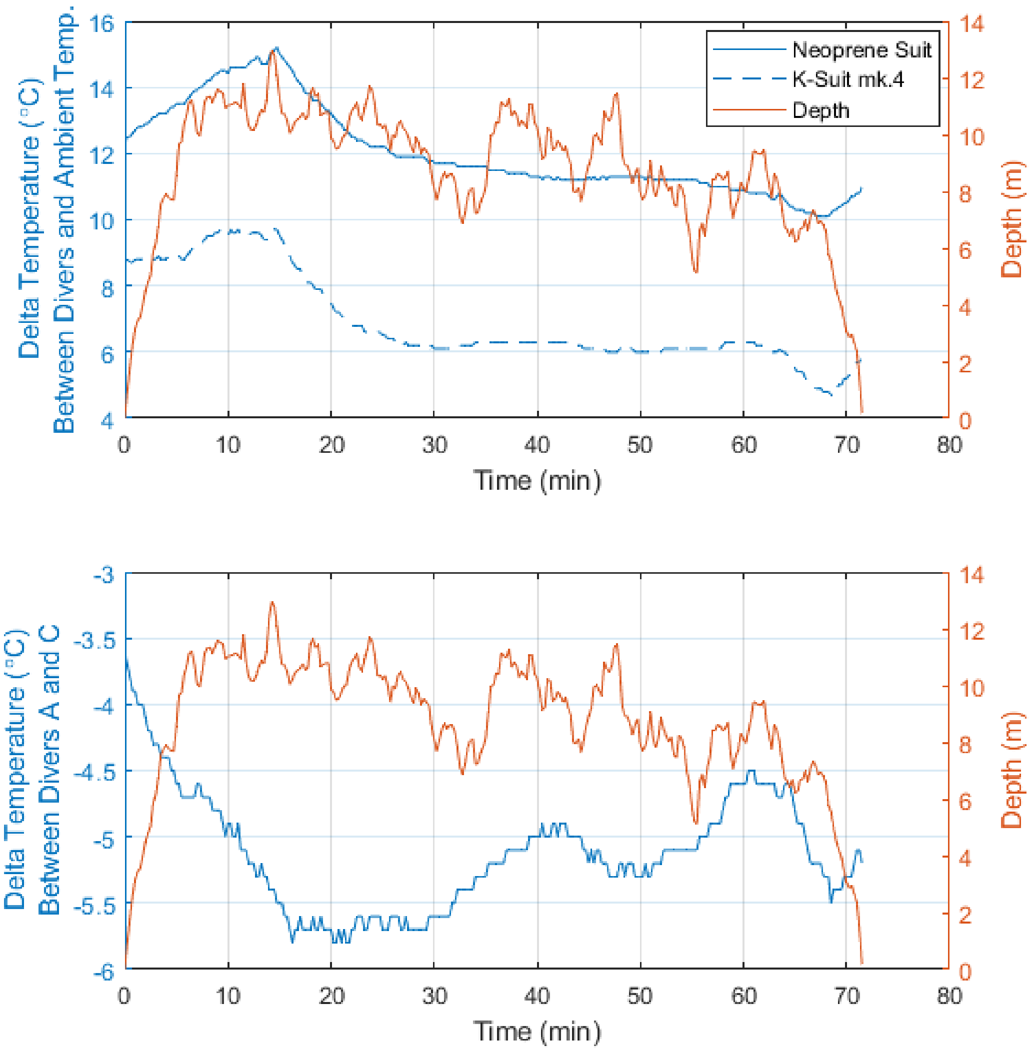


Figure 32. Delta Temperature between Divers and Ambient Temperature, along with Depth Measurements over Time (above). Delta Temperature between Divers A and C (below).

3. Dive 3: October 6, 2022—San Carlos Beach Breakwater

Diver A and Diver D, whose biometric information is shown in Figure 33 (right), went diving together at the same spot, on October 6. Diver D, who has a metabolic age of 37, was outfitted in a 3/5mm Aqualung wetsuit from the NPS Physics department facility, along with a 3mm vest underneath.

Diver D's method for locating his data recorder in dive 3 differed slightly from previous dives. He placed the diving device between the vest and the diving suit, as seen in Figure 33 (left), which assists in explaining why Diver A had a thermal advantage for the first 25 minutes of the dive, as seen in Figure 34.

Again, the temperatures of the divers largely followed the same patterns; however, in dive 3, the traditional diving wetsuit and vest combination did not provide any discernible thermal advantage over the K-Suit Mk.4.

After dive 3, Ms. Justice-Limes altered the neck zipper, the sleeves, and sufficiently shortened the abdominal and hip regions to significantly improve Diver A's suit fit. The K-Suit Mk.4 thermal insulation standards are thought to have been enhanced by these changes, because it helped to maintain a thinner water barrier between the diver and the suit. To be prepared for the following dive, nevertheless, it cost more than three weeks.

87.15 kg

From October 6, 2022 at 09:42

87.15kg Weight	24.4 BMI	18.2% Body Fat
71.30kg Fat-free Body Weight	15.9% Subcutaneous Fat	7 Visceral Fat
59.1% Body Water	52.9% Skeletal Muscle	67.70kg Muscle Mass
3.57kg Bone Mass	18.6% Protein	1909Kcal BMR

Figure 33. Location of Data Logger on Diver D (left). Biometrical Data of Diver D (right).

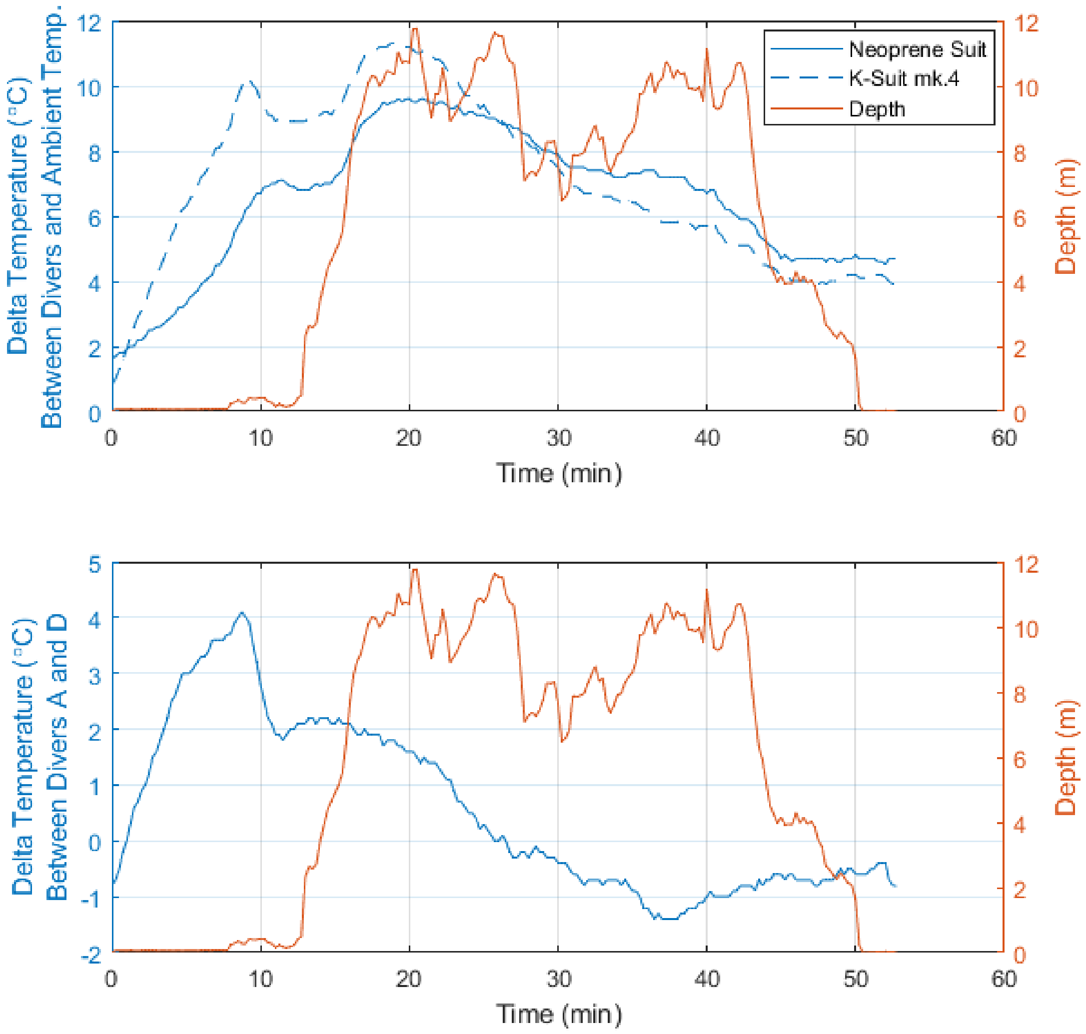


Figure 34. Delta Temperature between Divers and Ambient Temperature, along with Depth Measurements over Time (above). Delta Temperature between Divers A and D (below).

4. Dive 4: November 20, 2022—Monastery Beach

Dive 4 was intended to take place in a deeper area following K-Suit improvements. We were able to dive in Monastery Beach on November 20 since the swell was mild, and the divers had the opportunity to descend 30 meters immediately. A 7mm Long-John type wetsuit was worn by Diver E, whose biometric information is displayed in Figure 35. These wetsuits consist of two parts: the lower part is a single pants-vest, and the upper part is a jacket. That way Diver E was essentially wearing a 14mm thick wetsuit over the chest area, where the data logger was placed.

Figure 36 represents the delta temperature between divers and ambient temperature as well as the difference in temperature between Divers A and E over time. It is evident that, despite being in deeper water, where the ambient temperature drops, Diver A's maximum and lowest delta temperature differences have improved. This was also confirmed by Diver A, who thought the K-Suit mk.4 better fitting and leak-free.

86.95 kg

From November 20, 2022 at 09:10

86.95kg Weight	26.8 BMI	20.9% Body Fat
68.80kg Fat-free Body Weight	18.0% Subcutaneous Fat	10 Visceral Fat
57.1% Body Water	51.1% Skeletal Muscle	65.30kg Muscle Mass
3.44kg Bone Mass	18.0% Protein	1855Kcal BMR

Figure 35. Biometrical Data of Diver E.

Figure 36 further shows that after roughly 12 minutes of diving, Diver A has the lowest point of thermal insulation versus Diver E. Although a rise in Diver's A thermal insulation advantage during the deepest part of the dive was expected; it is evident that even after depth shrinkage, Diver's E wetsuit remained thick enough to maintain the thermal insulation. Meanwhile, Diver's A temperature gradually increased over time by

1.5 to 2° C, which may be related to the divers' biological characteristics and the improved performance of the K-Suit mk.4.

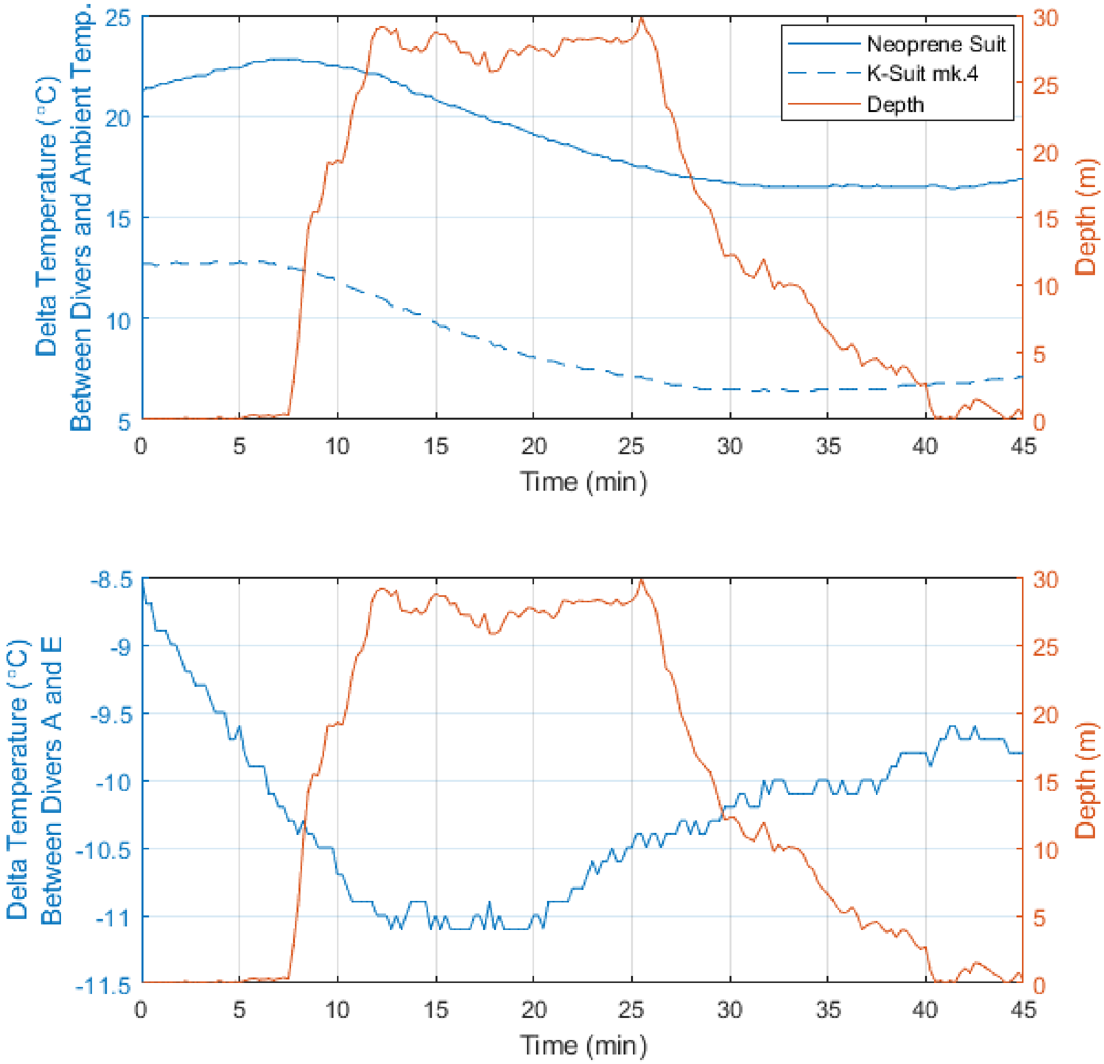
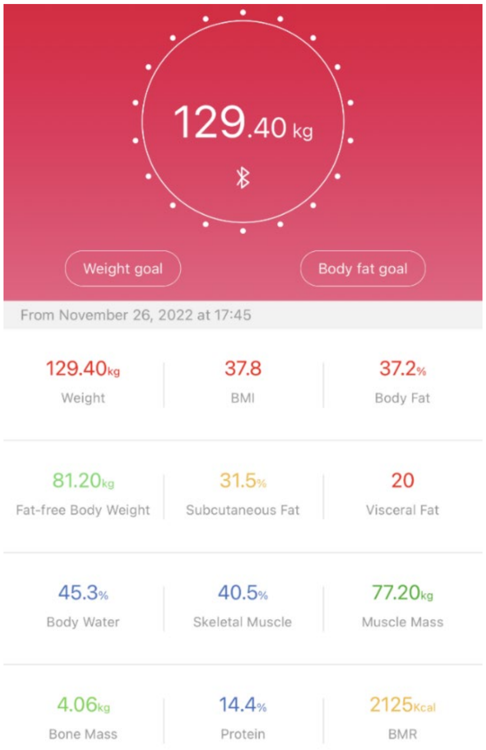


Figure 36. Delta Temperature between Divers and Ambient Temperature, along with Depth Measurements over Time (top). Delta Temperature between Divers A and E (bottom).

5. Dive 5: November 26, 2022—San Carlos Beach Breakwater

On November 26, I had the chance to meet Diver F, whose biometrical data appears in Figure 37. He has a metabolic age of 32 and used a 5mm wetsuit even during the fall. It was an excellent chance to compare the K-Suit Mk.4 with a 5mm wetsuit, and the results were impressive. The K-Suit had significantly better thermal insulation properties and kept Diver A almost 5° C warmer than the 5mm did for Diver F, as shown in Figure 38.

Also worth noting is that the K-Suit Mk.4 somewhat demonstrated the anticipated thermal insulation trend. Specifically, the K-Suit's thermal insulation advantage trend mirrors the depth trend from 6 to 14 and 23 to 28 minutes. By eliminating the first and last five minutes of the dive, from which it is difficult to draw conclusions, there is about a 70% match of those trends. Given that the dive took place in relatively shallow waters, this is a sufficient outcome.



From November 26, 2022 at 17:45

129.40kg Weight	37.8 BMI	37.2% Body Fat
81.20kg Fat-free Body Weight	31.5% Subcutaneous Fat	20 Visceral Fat
45.3% Body Water	40.5% Skeletal Muscle	77.20kg Muscle Mass
4.06kg Bone Mass	14.4% Protein	2125Kcal BMR

Figure 37. Biometrical Data of Diver F.

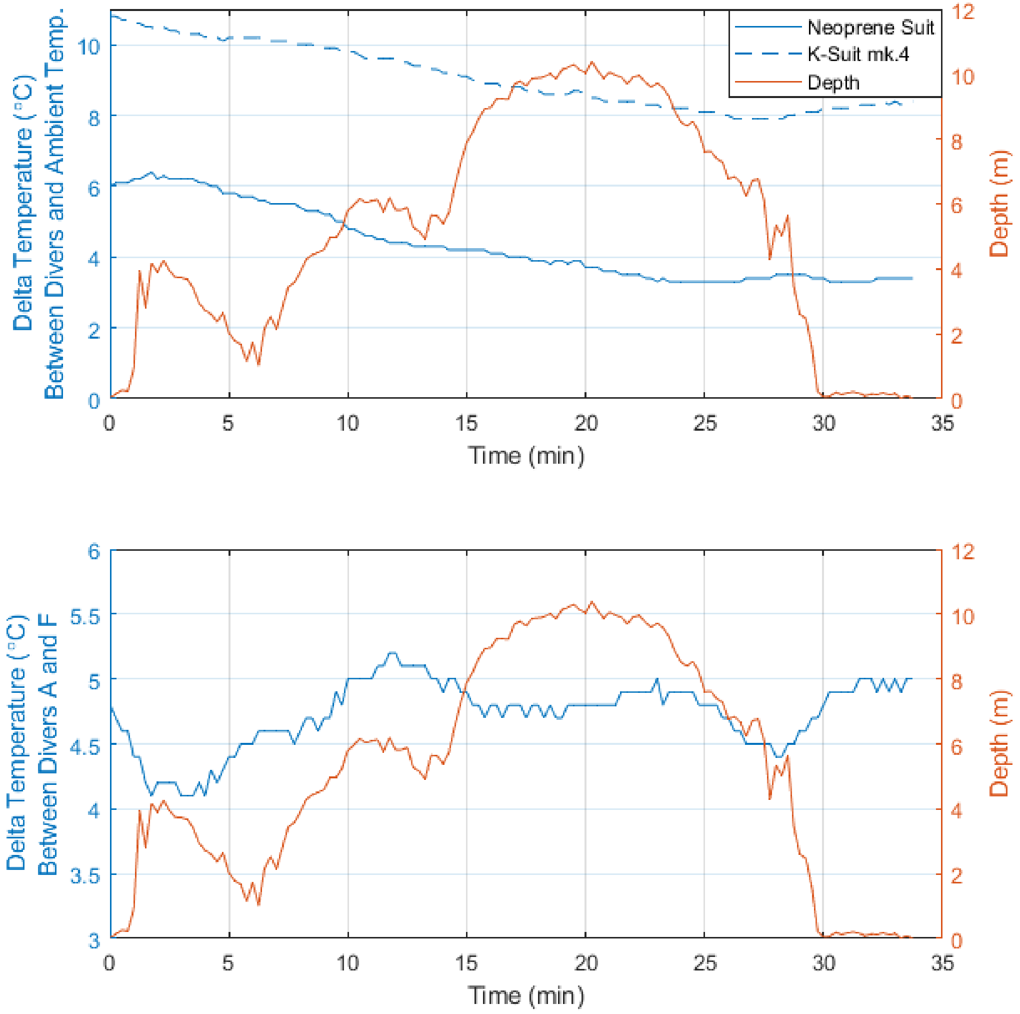


Figure 38. Delta Temperature between Divers and Ambient Temperature, along with Depth Measurements over Time (top). Delta Temperature between Divers A and F (bottom).

6. Dive 6: November 27, 2022—Carmel River Beach

The final dive experiment was conducted on November 27 in Carmel River Beach with the same diving buddy who had participated in dive 4 on Monastery Beach. It was intended to be a deep-water dive as well, but the surf was more than we had anticipated and required divers A and E to swim hard and for a long time to reach a deep area. This dive pattern and effort is a bit reminiscent of the infiltration dives performed by Naval

Special Warfare Teams, where the divers are concentrated on maintaining a precise direction of movement and exerting much more effort than they would on a regular recreational dive. According to Diver A, the ergonomics of the K-Suit Mk.4 during this sort of dive were as great as they were throughout all of the prior dives.

We rented a standard 7mm wetsuit from the Monterey Bay Scuba Shop by San Carlos Beach parking since it would be unfair to compare the K-Suit with a Long-John style 7mm wetsuit, as we did during dive 4.

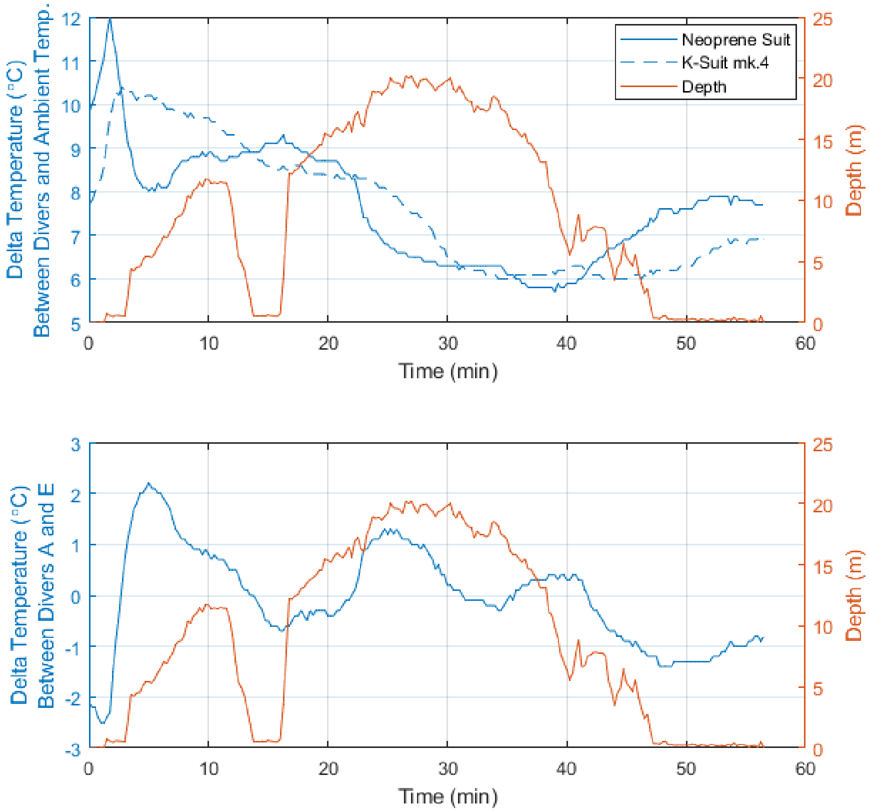


Figure 39. Delta Temperature between Divers and Ambient Temperature, along with Depth Measurements over Time (top). Delta Temperature between Divers A and E (bottom).

The results were in favor of the K-Suit again. First, the K-Suit had approximately the same thermal insulation as the 7mm did since the average delta temperature between the two suits was -0.05° C. Second, with the exception of the six to ten minute and 35 to 40 minute intervals, the thermal insulation advantage trend of the K-Suit almost matches the depth trend throughout the dive.

C. DIVE EXPERIMENTS SUMMARY

The overall picture of the data gathered throughout all the dives is shown in Table 1. Given the range of Delta Temperature in Table 1, it can be confidently concluded that the K-Suit performed better after dive 3, which involved changes to the neck zipper, sleeves, and abdominal area.

Table 1. Experimental Dives Data Summary.

	Diving Buddy	Buddy's Wetsuit	Avg. Depth [m]	Avg. Ambient Temp. [°C]	Avg. K-Suit Temp. [°C]	K-Suit Range of Delta Temp. [°C]	Avg. Delta Temp. between Suits [°C]
Dive 1	B	7mm and 2mm vest	8.55	15.04	24.12	7.9	N/A
Dive 2	C	7mm and 3mm vest	8.75	16.59	23.51	5	-5.12
Dive 3	D	3/5mm and 3mm vest	7.02	13.79	21.40	7.4	0.36
Dive 4	E	7mm Long John	16.95	11.72	19.77	6.1	-10.43
Dive 5	F	5mm	5.95	12.02	21.19	2.9	4.70
Dive 6	E	7mm	11.07	12.12	19.92	4.4	0.23

Table 2 compares the K-suit Mk.4 with each dive buddy's wetsuit after merging the Delta Temperature data from Table 1 with the underwater diving experience of the divers in terms of ergonomics and buoyancy fluctuation. Green color and light green represent the K-Suit's significant and moderate competitive advantages over wetsuits, respectively. Red denotes a severe disadvantage of the K-Suit, whereas orange denotes a moderate disadvantage.

Table 2. K-Suit Comparison with Experimental Dives' Wetsuits.

	Diving Buddy	Buddy's Wetsuit	Ergonomics	Constant buoyancy	Thermal Insulation
Dive 1	B	7mm and 2mm vest	🟩	🟩	N/A
Dive 2	C	7mm and 3mm vest	🟩	🟩	🟧
Dive 3	D	3/5mm and 3mm vest	🟩	🟩	🟩
Dive 4	E	7mm Long John type	🟩	🟩	🟥
Dive 5	F	5mm	🟩	🟩	🟩
Dive 6	E	7mm	🟩	🟩	🟩

D. FUTURE WORK

The author would advise conducting further dives with specific requirements to draw safe conclusions and support the superiority of the K-Suit Mk.4. The prototype should only be compared against a 7mm standard wetsuit, and if at all feasible, by the same diving partner. To best demonstrate the benefit of the K-Suit's incompressibility, the dives should be carried out in deep water diving locations.

The diver's sonar shielding provided by solid ceramic composite parts was not tested in this study since there was not enough time. Hence, that would present a chance for future students to conduct detailed experiments.

Finally, it would be useful to employ hollow ceramic beads, as seen in Figure 15, to construct a different wetsuit. In terms of thermal insulation, those beads are slightly less effective than the hollow glass microsphere beads, but they are closer to neutral buoyancy. Furthermore, if given the chance to develop a second suit, the author would aim to create thinner composite components that would cover larger regions without covering the joints to retain mobility.

V. CONCLUSION

In this thesis, the author attempted to develop a composite diving suit that would optimally meet the needs of Navy Special Warfare operators. The K-Suit Mk.4 prototype was built by attaching two layers of composite materials on a 3mm neoprene wetsuit base. The first composite layer consisted of 8mm thick glass microspheres mixed with a polymer, and the second thinner layer was made from solid ceramic beads combined with the same polymer.

The K-Suit Mk.4 prototype's goal is to support high agility and provide superior ergonomics while offering improved thermal insulation, regardless of operational depth. Additionally, it is intended to be neutrally buoyant, unaffected by high pressure at great depths, and to provide acoustic protection by reflecting underwater sound waves off the ceramic composite components.

Six dive experiments were conducted to test the prototype's performance. Although the first three dives took place in shallow waters and the diving suit needed extra modifications to minimize leaks, there were enough experiments to confirm that the K-Suit Mk.4 performs better than a typical 7mm diving wetsuit in terms of thermal insulation, ergonomics, and constant neutral buoyancy.

Future research on sonic protection is advised since this might reveal additional benefits of the K-Suit mk.4 for Naval Special Warfare operators. More research in deep water would also make it clearer that thermal insulation tends to increase with depth, when compared with a typical 7mm diving wetsuit.

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APPENDIX A. COMPOSITE PIECES' MIXING WEIGHTS

Table 3. Composite Pieces' Mixing Weights.

Piece	Polymer Base [gr]	Polymer Curing Agent [gr]	Glass Microspheres [gr]	Cups needed	Date / Time	Hours Spent
Glass Microsphere Pieces						
Left Forearm	90.00	9.00	9.21	2	Feb. 01st 0800-0930	01.30
	90.70	9.02	9.10			
Left Shoulder	90.48	9.24	9.13	2.2	Feb. 26th 0800-0930	01.30
	90.67	9.97	9.41			
Left Shin	90.24	9.13	10.03	4	Mar. 15th 1230-1430	02.00
	98.17	9.90	11.05			
	94.83	9.49	10.60			
	90.25	9.06	10.04			
Left Thigh	90.15	9.25	8.93	2.5	Feb. 25th 0930-1130	03.00
	90.26	9.10	9.20			
	90.23	9.11	9.58			
Left Back	90.23	9.10	10.01	3	Mar. 15th 1730-1930	02.00
	94.82	9.48	10.01			
	93.78	9.63	10.35			
Left Chest	90.10	9.09	10.14	3	Apr. 01st 1500-1700	02.00
	90.16	9.04	10.14			
	99.80	10.02	11.10			
AB	90.08	9.00	10.24	1.8	Feb. 25th 1130-1230	01.00
	93.60	9.33	10.20			
Lower Back	90.00	9.09	10.00	3.5	Apr. 07th 1530–1645	01.15
	90.00	9.06	10.00			
	90.00	9.00	10.00			
	48.00	4.80	5.14			
Right Forearm	90.40	9.03	9.48	2	Mar. 22nd 2000-2200	02.00
	91.55	9.07	9.78			
Right Shoulder	95.14	9.68	10.38	2.7	Apr. 01st 1700-1900	02.00
	94.00	9.40	10.40			
	90.00	9.13	10.00			
Right Shin	90.58	9.16	9.98	4.5	Apr. 04th 0900–1145	02.45
	90.13	9.04	9.99			
	90.46	9.00	10.03			
	91.65	9.17	10.04			
Right Thigh	93.50	9.35	10.00	2.5	Apr. 06th 1000–1145	01.45
	90.00	9.00	10.00			

	45.00	4.50	5.00			
Right Back	91.88	9.16	10.00	3	Apr. 06th 1950–2200	02.10
	94.33	9.37	10.30			
	91.30	9.90	10.00			
Right Chest	90.00	9.00	10.00	3	Apr. 07th 1415–1530	01.15
	90.00	9.00	10.00			
	94.40	9.44	10.05			
Ceramic Pieces						
1st Pan	104.40	10.47	135.00	4.5	Apr. 22nd 1000-1200	02.00
	104.40	10.30	137.00			
	101.60	10.00	135.00			
	105.00	10.50	148.00			
	52.00	5.00	70.00			
2nd Pan	102.80	10.24	138.56	4	July 18th 1000-1200	02.00
	103.53	10.32	137.21			
	102.43	10.26	139.35			
	102.87	10.29	140.32			
3rd Pan	100.40	10.06	132.75	4	July 19th 1000-1200	02.00
	103.43	10.43	138.15			
	100.60	10.05	134.20			
	100.85	9.98	133.60			
4th Pan	103.90	10.37	136.56	4	July 20th 1000-1200	02.00
	102.32	10.19	136.51			
	105.14	10.52	141.25			
	101.98	10.13	135.30			
5th Pan	93.00	8.98	120.00	4	July 22nd 1000-1200	02.00
	91.37	9.20	122.00			
	92.98	9.05	120.00			
	90.52	9.17	120.00			
6th Pan	87.65	8.59	114.00	4	Jul. 25th 1000-1200	02.00
	95.70	9.59	127.00			
	101.10	10.11	134.00			
	90.50	9.15	120.00			
7th Pan	90.70	9.05	120.00	3.5	Jul. 26th 1000-1200	02.00
	95.30	9.55	127.00			
	95.70	9.59	126.44			
	49.44	5.06	67.45			
8th Pan	90.20	9.07	120.00	3.5	Jul. 27th 1000-1200	02.00
	91.50	9.13	120.00			
	90.30	8.97	120.00			
	45.00	4.50	60.00			

APPENDIX B. COMPOSITE PIECES' WEIGHTS

Table 4. Composite Pieces' Weights and Buoyancy Testing Results.

Pieces	Weight Needed to Become Negative Buoyant [gr]	Avg. Area [cm^2]	Glass Avg. Thickness [mm]	Ceramic Avg. Thickness [mm]	Glass Weight [gr]	Ceramic Weight [gr]
R. Forearm	30	190	10.37	7.12	108.50	231.00
L. Forearm	30	191	10.45	4.94	107.00	182.00
R. Shoulder	100	287	10.48	4.94	170.56	236.93
L. Shoulder	120	275	10.52	4.86	167.22	237.25
R. Chest	0	429	6.83	5.33	172.12	420.40
L. Chest	20	386	7.44	5.42	198.00	402.00
R. Back	30	464	9.66	5.65	257.80	396.74
L. Back	60	360	9.31	5.65	221.00	328.00
R. Lower Back	30	163	8.42	5.68	84.78	143.50
L. Lower Back	30	159	11.62	5.22	114.00	149.50
R. Thigh	50	348	7.00	5.11	187.00	309.00
L. Thigh	50	378	6.32	4.71	213.00	307.00
R. Back Thigh	20	372	10.07	5.48	269.00	274.00
L. Back Thigh	50	319	9.45	5.73	221.00	253.05
R. Shin	130	483	11.52	4.44	315.00	339.71
L. Shin	140	438	11.12	4.04	280.00	275.00
R. Back Shin	40	245	11.74	4.70	189.00	191.00
L. Back Shin	50	201	11.69	4.21	129.00	145.70
AB	0	309	6.12	5.44	104.50	226.00
TOTAL	**980**	**5997**			**3,508.48**	**5,047.78**

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LIST OF REFERENCES

[1] F. Förster, H. Riemer, and R. Kuper, "The 'Cave of Beasts' (Gilf Kebir, SW Egypt) and its chronological and cultural affiliation: Approaches and preliminary results of the Wadi Sura project," presented at the International Colloquium, Brussels, Jun. 2010.

[2] R. Strandell, "Ancient history of diving," *Suomen Sukellus-historiallinen yhdistys*, Jul. 19, 2019 [Online]. Available: https://www.sukellushistoriallinenyhdistys.fi/ancient-diving/

[3] R. Southey, *The Iliad of Homer*. New York: D. Appleton & Co., 2005 [Online]. Available: https://www.gutenberg.org/ebooks/16452

[4] Susan, "History of the Sponge Divers of Kalymnos Greece," *Greeker than the Greeks*, blog, Aug. 29, 2018 [Online]. Available: https://greekerthanthegreeks.com/2018/08/the-naked-sponge-divers-of-kalymnos.html

[5] US Department of Commerce – Office of Marine and Aviation Operations, *NOAA Diving Manual*, 5th ed., FL: Best Publishing Company, 2013.

[6] C. E. Ioannidou, "Diving in Ancient Greece during the late archaic and classical period (6th–4th century BC)," *Archaeology and Science*, vol. 10, pp. 111–119, 2014 [Online]. Available: https://doi.org/10.18485/ARHE_APN.2014.10.6.

[7] *U.S. Navy Diving Manual,* SS521-AG-PRO-010, Naval Sea Systems Command, Washington, DC, USA, 2016 [Online]. Available:https://www.navsea.navy.mil/Portals/103/Documents/SUPSALV/Diving/US%20DIVING%20MANUAL_REV7.pdf?ver=2017-01-11-102354-393

[8] USNUM, "MK V diving rig," *U. S. Naval Undersea Museum*, blog, Sep. 19, 2016 [Online]. Available: https://navalunderseamuseum.org/mk-v/

[9] "US Navy Mark V diving helmet," *Diving Heritage*, May 13, 2012 [Online]. Available: https://www.divingheritage.com/markv.htm

[10] National Inventors Hall of Fame, "Jacques-Yves Cousteau," 2022 [Online]. Available: https://www.invent.org/inductees/jacques-yves-cousteau

[11] S. Ninokawa and K. Nordham, "Discovery of caisson disease: A dive into the history of decompression sickness," *Proc (Bayl Univ Med Cent)*, vol. 35, no. 1, pp. 129–132, Sep. 2021 [Online]. Available: https://doi.org/10.1080/08998280.2021.1967021

[12] DAN, "Top 5 factors that increase your risk of the bends," Divers Alert Network, blog, July 14, 2020 [Online]. Available: https://dan.org/safety-prevention/diver-safety/divers-blog/top-5-factors-that-increase-your-risk-of-the-bends/

[13] J. Hooper, *Weapons Physics*. Monterey, CA, USA: Naval Postgraduate School, 2020.

[14] C. Ermine and J. Gaspin, "Swimmer safe standoffs from underwater explosions." Navy Science Assistance Program, Arlington, VA, 1974, Rep. No. NOLX 80.

[15] J. H. Young, "Investigation of acoustic characteristics and DB reduction of microsphere-based paneling on diving wetsuits," M.S. thesis, Dept. of Physics, NPS, Monterey, CA, USA, 2021 [Online]. Available: https://calhoun.nps.edu/handle/10945/67838

[16] R. J. Yardley, "Underwater explosive recovery," Special Operations Rescue Tactical Interdiction Expeditions - S.O.R.T.I.E. [Online]. Available: http://www.wateroperations.com/sortie/issue1/article12.htm

[17] J. Kreuzer, "Body temperature: normal ranges & how to measure," Cosinuss, blog, 2021 [Online]. Available: https://www.cosinuss.com/en/measured-data/vital-signs/body-temperature/

[18] H. Ornhagen, "Thermal problems in diving," Tokyo, Japan, Nov. 2004.

[19] *Drowning Management*, CPG ID:64, Joint Trauma System, Houston, TX, Oct. 27, 2017. Accessed Oct. 20, 2022 [Online]. Available: https://books.allogy.com/web/tenant/8/books/bb1869bb-b62d-418b-8ae7-b183735131e0/

[20] J. A. Downing, "Hypothermia: Understanding and prevention," Minnesota Sea Grant, University of Minnesota. Accessed: Oct. 15, 2022 [Online]. Available: https://seagrant.umn.edu/programs/recreation-and-water-safety-program/hypothermia

[21] D. L. Dekker, "1839 Augustus Siebe." Diving Helmet. Accessed Oct. 27, 2022 [Online]. Available: https://www.divinghelmet.nl/divinghelmet/1839_Augustus_Siebe.html

[22] 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://calhoun.nps.edu/handle/10945/59632

[23] A. 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/citations/AD1114573

[24] Edubilla, “Hugh Bradner biography, list of Hugh Bradner inventions.” Accessed Oct. 27, 2022 [Online]. Available: http://www.edubilla.com/inventor/hugh-bradner/

[25] Mares, “Active heating vest,” 2022 [Online]. Available: https://www.mares.com/en_FI/active-heating-vest-5

[26] 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/citations/AD1126514

[27] A. R. Kwong-Wright, “Microsphere-based composite wetsuit for incompressible passive thermal insulation,” M.S. thesis, Dept. of Physics, NPS, Monterey, CA, USA, 2021 [Online]. Available: https://calhoun.nps.edu/handle/10945/67757

[28] A. Waldron, “Improving the flexibility and thermal protection of a diving wetsuit,” M.S. thesis, Dept. of Mechanical and Aerospace Engineering, NPS, Monterey, CA, USA, 2022 [Online]. Available: https://calhoun.nps.edu/handle/10945/70779

[29] F. J. Frost, “Scyllias: Diving in antiquity,” *Greece & Rome*, vol. 15, no. 2, pp. 180–185, Oct. 1968 [Online]. Available: https://www.jstor.org/stable/642431

[30] K. Mavraganis, “Σκυλλίας και Ύδνα: Οι πρώτοι κολυμβητές «υπεραποστάσεων» της ιστορίας και η παράτολμη αποστολή τους εναντίον των Περσών,” [Scyllias and Hydna: History’s First “Ultra-Distance” Swimmers and Their Daring Mission Against the Persians] HuffPost Greece, Aug. 27, 2020 [Online]. Available: https://www.huffingtonpost.gr/entry/skellias-kai-edna-oi-protoi-kolemvetes-eperapostaseon-tes-istorias-kai-e-paratolme-apostole-toes-enantion-ton-person_gr_5f475a23c5b697186e31190a

[31] M. Stoukas, “Η ναυμαχία του Αρτεμισίου (480 π.Χ.),” [The naval battle of Artemisius (480 BC)] ProtoThema, Mar. 19, 2017 [Online]. Available: https://www.protothema.gr/stories/article/663854/i-naumahia-tou-artemisiou-480-ph/

[32] Navy SEALs, “Navy SEAL history.” Accessed Sep. 04, 2022 [Online]. Available: https://navyseals.com/nsw/navy-seal-history/

[33] Xavier University, “Captain Phil H. Bucklew - A lifetime of service.” Accessed Nov. 04, 2022 [Online]. Available: https://www.xavier.edu/veterans/about-us/donate

[34] “US Navy explosive ordnance disposal (EOD) divers,” Wikipedia. Accessed Nov. 20, 2022 [Online]. Available: https://commons.wikimedia.org/wiki/File:US_Navy_explosive_ordnance_disposal_(EOD)_divers.jpg

[35] S. Atlamazoglou, “79 years after the first submarine-launched commando raid, Navy SEALs say it hasn’t gotten any easier,” Business Insider, Sep. 17, 2021 [Online]. Available: https://www.businessinsider.com/navy-seals-explain-why-submarine-launched-commando-raids-are-tough-2021-9

[36] E. Davis, “US Navy SEALs: SDV1,” Special Operations, Dec. 24, 2013 [Online]. Available: https://specialoperations.com/28311/us-navy-seals-sdv1/

[37] SOFREP, “SEAL Delivery Vehicles: The SEAL Teams’ secret weapon,” August 01, 2019 [Online]. Available: https://sofrep.com/news/seal-delivery-vehicles-the-seal-teams-secret-weapon/

[38] K. W. Rehn and P. K. Riggs, “Non-Lethal swimmer neutralization study,” Defense Technical Information Center, Fort Belvoir, VA, May 2002 [Online]. Available: /tardir/tiffs/a406644.tiff (dtic.mil)

[39] T. Ball, “Still the one: Great Power Competition and Special Operations,” Foreign Policy Research Institute, Jul. 10, 2020 [Online]. Available: https://www.fpri.org/article/2020/07/still-the-one-great-power-competition-and-special-operations-forces/

[40] T. Trask, M. Clark, and S. Bradin, “The role of special operations forces in a ‘Great Power Conflict,’” Military Times, May 04, 2020 [Online]. Available: https://www.militarytimes.com/opinion/commentary/2020/05/04/the-role-of-special-operations-forces-in-a-great-power-conflict/

[41] A. Saxena, “The return of Great Power Competition to the Arctic,” The Arctic Institute - Center for Circumpolar Security Studies, Oct. 22, 2020 [Online]. Available: https://www.thearcticinstitute.org/return-great-power-competition-arctic/

[42] S. Atlamazoglou, “Navy SEALs and Army Green Berets are training for a new, frigid battlefield after 2 decades in the desert,” Business Insider, May 11, 2022 [Online]. Available: https://www.businessinsider.com/navy-seals-army-green-berets-train-for-frigid-arctic-battlefield-2022-5

[43] SeventhWave, “Neoprene: a brief history.” Accessed Sep. 01, 2022 [Online]. Available: https://www.seventhwave.co.nz/wetsuits101/Neoprene+Info/Neoprene+a+brief+history.html

[44] P. Zarifeh, *Neoprene Inside Story,* New Zealand: Seventhwave, 2012 [Online]. Available: https://www.seventhwave.co.nz/site/seventhwave/files/Neoprene_Inside_Story.pdf

[45] Invention City, “Hugh Bradner - Neoprene wetsuit.” Accessed Oct. 31, 2022 [Online]. Available: https://www.inventioncity.com/patent-news/hugh-bradner-neoprene-wetsuit

[46] D. Slater, “Who made that wet suit?,” *The New York Times*, Jul. 03, 2014 [Online]. Available: https://www.nytimes.com/2014/07/06/magazine/who-made-that-wet-suit.html

[47] Engineering ToolBox, “Solids, liquids and gases - Thermal Conductivities,” 2003 [Online]. Available: https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

[48] SRFACE, “Wetsuit neoprene.” Accessed Oct. 31, 2022 [Online]. Available: https://srface.com/knowledge-base/wetsuit-neoprene/

[49] Amazon, “BIGZFABRIC® Neoprene bonded sponge waterproof wetsuit fabric black.” Accessed Oct. 20, 2022 [Online]. Available: https://www.amazon.com/BIGZFABRIC-Neoprene-Waterproof-Wetsuit-Fabric/dp/B06X19DRRY/ref=sr_1_8?crid=29Z62FUDD28DZ&keywords=1%2Bmm%2Bneoprene&qid=1668990644&sprefix=1%2Bmm%2Bneoprene%2Caps%2C172&sr=8-8&th=1

[50] C. Brummet and N. R. Raju, “An investigation into the use of neoprene (a red listed material) for soundproofing,” Nov. 30, 2010 [Online]. Available: https://dx.doi.org/10.14288/1.0108313

[51] Glomex, “Neoprene.” Accessed Sep. 17, 2022 [Online]. Available: https://glomexusa.com/neoprene

[52] 3M, *Glass Bubbles K Series, S Series and iM Series*, 98–0212-3859-1, 2013 [Online]. Available: https://multimedia.3m.com/mws/media/91049O/3m-glass-bubbles-k-s-and-im-series.pdf

[53] SICT - Le Syndicat des Industriels des Ceramiques Techniques, “Thermal conductivity / thermal insulation.” Accessed Sep. 19, 2022 [Online]. Available: https://ceramique-technique.com/en/properties/thermal-conductivity-thermal-insulation-thermal-properties

[54] Hy-Tech Thermal Solutions, “Insulating additive thermacels.” Accessed Sep. 19, 2022 [Online]. Available: https://hytechsales.com/INSULATING-ADDITIVE--THERMACELS_p_18.html

[55] 3M, *Ceramic Microspheres White Grade W-610*, 2022 [Online]. Available: https://www.3m.com/3M/en_US/p/d/b40065230/

[56] A. Vepsäläinen, J. Pitkänen, and T. Hyppänen, *Fundamentals of heat transfer*. Finland: Lappeenranta University of Technology, 2012 [Online]. Available: https://lutpub.lut.fi/bitstream/handle/10024/86241/HTfundamentals_LectureNotes_Official.pdf?sequence=1&isAllowed=y

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