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THESIS

**MICROSPHERE-BASED PASSIVE MATERIAL FOR
LOW-TEMPERATURE DIVING SUITS**

by

Jonathan M. Brown

June 2018

Thesis Advisor:

Emil P. Kartalov

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**MICROSPHERE-BASED PASSIVE MATERIAL FOR LOW-TEMPERATURE
DIVING SUITS**

Jonathan M. Brown
Captain, United States Marine Corps
BS, U.S. Naval Academy, 2011

Submitted in partial fulfillment of the
requirements for the degree of

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from the

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Approved by: Emil P. Kartalov
Advisor

Kevin B. Smith
Chair, Department of Physics

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ABSTRACT

Navy divers and dive-qualified personnel are often required to operate in cold water. The threat of hypothermia and other health concerns limits the time a diver is allowed in the water. The neoprene wetsuit is the primary material used for protection in low temperature conditions. Small pockets of air within the neoprene create a thermally insulating layer of air between the diver and the ocean. As the individual descends underwater, the increase of static pressure on the wetsuit causes the protective air pockets to shrink. This sharply lowers the overall thermal resistance of the wetsuit. By replacing the insulating air pockets with rigid glass microspheres, changes in depth had significantly less negative influence on the thermal resistivity and buoyancy of the fabricated material. Resulting experimental data related thermal resistivity to volumetric fraction of microspheres in the polymer. This effort ultimately proved the superior thermal properties of the fabricated composite over neoprene and expanded future possibilities for passive thermal protection in low-temperature waters.

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LIST OF ACRONYMS AND ABBREVIATIONS

cm	centimeter
EOD	Explosive Ordnance Disposal
FSW	feet seawater
mm	millimeter
NEDU	Naval Experimental Diving Unit
NCTRU	Navy Clothing and Textile Research Unit
PDMS	polydimethylsiloxane
psi	pounds per square inch
SEAL	Sea, Air, and Land special warfare
UDT	Underwater Demolition Team

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I. INTRODUCTION

A. BACKGROUND

The earliest documented professional dive operations date back 5,000 years and have maintained pervasive application in military operations [1]. One of the most prominent legends is detailed by the Greek philosopher Aristotle, who recorded Alexander the Great utilizing an inverted barrel as a makeshift diving bell in order to hide during the Battle of Tyre [2]. Throughout these millennia, the applicability of military diving drastically increased with advancements in naval fleet designed to both control the open sea and deploy military forces from sea to land. The past 100 years particularly revealed an unprecedented use of the littoral space—the region of terrain lying along a shore of a body of water—to project massive military power ashore. The world’s population continues to concentrate toward the coastline with an estimated 40% currently living within 100 kilometers of the shore [3]. The littorals are subsequently becoming increasingly contested and form critical access points for strategic military influence. This reality demands concurrent effort to develop technologies that ensure success for the U.S. Navy as it continues to operate throughout the world’s oceans and coastline.

1. U.S. Naval Application

The United States has built a naval fleet that is unprecedented both in technology and dominance. Expeditionary force structure of the Navy-Marine Corps team preserves national interests via the seven seas’ and validates its merit through the successful conduct of amphibious operations across the spectrum of conflict. In order to maintain control of and access to littorals, the U.S. Navy continually leverages the subsurface environment to employ its forces and equipment. Beach reconnaissance, personnel insertion and extraction, explosive ordinance disposal/mine clearance, and underwater ship-hull security sweeps are but a few of the missions demanded by the current operating environment.

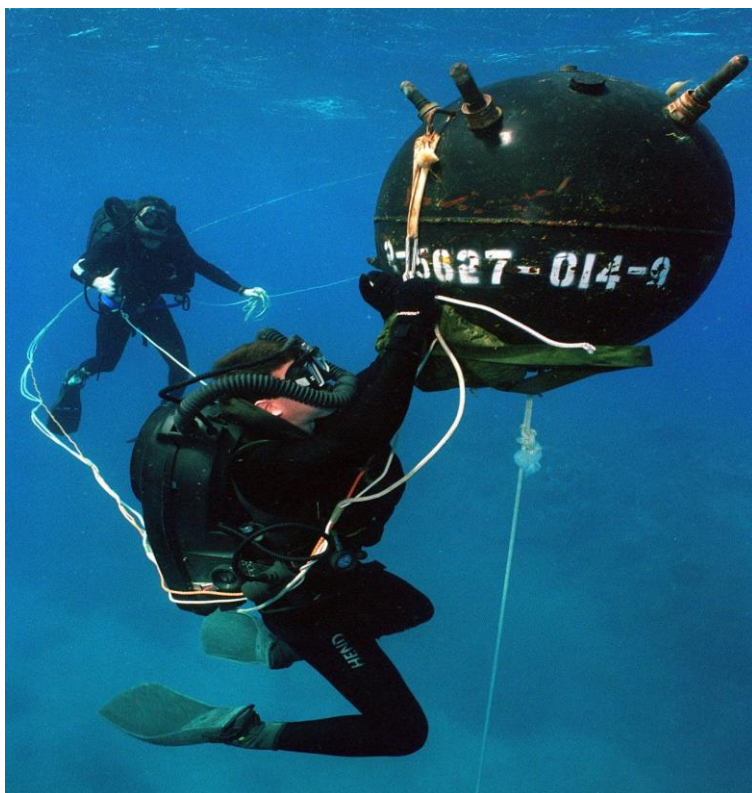


Figure 1. U.S. Navy Explosive Ordnance Disposal disarming underwater training mine during exercise. Source: [4].

Furthermore, the ocean is a relentless foe to sustaining a well-maintained, operational fleet. Navy diving and salvage provide critical repairs and preventative maintenance to naval shipping without the significant labor and time demands of dry-docking a vessel.



Figure 2. U.S. Navy diver conducts underwater maintenance on ship.
Source: [5].

Therefore, dive technology must continue to mitigate the negative effects of the unforgiving aquatic environment in order to improve the capabilities of U.S. military dive operations.

2. History of U.S. Navy Diving

The U.S. Navy has a longstanding history in the development and testing of what is now called the self-contained underwater breathing apparatus (scuba). In 1912, Chief Gunner George D. Stillson spearheaded the first human testing to officially validate dive tables designed to prevent nitrogen poisoning by gradual recompression during surfacing [6]. Such tables are the foundation for modern recreational and professional dive operations. Stillson also used this opportunity to expand Navy dive equipment and pushed beyond the traditional depth of 60 feet seawater (FSW) that limited most divers. The program eventually set the mark at 274 FSW and was the impetus for a critical salvage operation six months later after the sinking of the submarine USS *F-4* that pushed divers to 304 FSW [6].



Figure 3. U.S. Navy diver wearing Mark V rig (developed in 1916).
Source: [7].

From 1912–1939, the U.S. Navy continued explosive growth in its submarine force which suffered a myriad of accidents requiring the Navy dive community to expand its capabilities in underwater rescue and salvage. This period cemented the need for formalized training that prepared individuals to operate at depths that often incurred adverse physiological effects. World War II continued to validate the need for a capable, adaptable Navy dive force. During and immediately following the Battle at Pearl Harbor, Navy divers logged an estimated 16,000 hours through 4,000 dives in rescue and salvage efforts [1].



Figure 4. U.S. Navy divers salvaging the USS *Oklahoma* following Battle of Pearl Harbor. Source: [8].

Combat operations during the Second World War also demanded the need for underwater mine clearance and obstacle removal, resulting in the development of the Navy's Underwater Demolition Teams (UDT). UDT would later split into the Explosive Ordnance Disposal (EOD) and Sea, Air, and Land (SEAL) special warfare communities which are now the United States military's premier force in combat dive operations. From World War II to the present day, the Navy diver missions continue to diversify along with its supporting establishments designed to further Navy dive technology. Institutions to include the Navy Experimental Diving Unit (NEDU), Navy Medical Research Institute, and Naval Diving and Salvage Training Center are foremost authorities on dive technology and training.



Figure 5. Students at Naval Diving and Salvage Training Center. Source: [9]

The dangers inherent to dive operations require constant attention and will continue to catalyze further investment in equipment that ensures the success of the brave individuals who execute real-world missions in support of U.S. national interests.

B. CURRENT CHALLENGES AND SOLUTIONS

Navy divers are presented with a host of physiological challenges due to the pressure and temperature of the subsurface environment. Nitrogen narcosis and hypothermia are primary concerns that can debilitate or kill their victims. The risk of the latter can severely limit the time a diver remains submerged and inhibit the success of dive operations in all regions of the world. In order to mitigate this risk, thermal insulation is provided via foamed neoprene wetsuits and rubberized dry suits. Both methods of protection are designed to maintain a protective layer between the skin and water in order to prevent heat loss.

1. Water and Hypothermia

The Mayo Clinic defines hypothermia as “a medical emergency that occurs when your body loses heat faster than it can produce heat, causing a dangerously low body temperature” [10]. The threat of hypothermia increases during prolonged exposure to increasingly cold ambient temperatures. Water exacerbates this issue with a specific heat 1000 times higher than

air and heat conduction 27 times faster underwater [11]. While underwater temperatures vary greatly throughout the globe, colder water of higher salinity will always gather below a layer of less dense, warmer surface water. Thus, there is an inevitable depth at which the ambient temperature can dangerously lower a human's core temperature. Some of these depths occur beyond the vast majority of naval dive operations. However, given the geographical span of military dive missions, many personnel operate in environments that threaten hypothermia or intolerable discomfort at common operating depths.



Figure 6. Explosive ordnance disposal technician during ice dive in northern Norway. Source: [12].

2. Passive and Active Thermal Protection

Passive thermal insulation prevents heat loss in free-swimming divers by slowing heat transfer through the skin into the water. Thicker passive barriers have greater resistance to heat transfer, which improves the body's ability to regulate its internal temperature with less energy output. Wetsuits are the most widely used method for passive thermal protection and are commonly made of foamed neoprene: a layered rubber that is infused with tiny air pockets to create the skin-water boundary. It traps a small layer of water against the skin, which is warmed by body heat to serve as the insulator.

Conversely, a dry suit has a rubber shell with a thermal layer that prevents any direct contact between skin and water. While the dry suit is considered the highest standard of protection for low temperature diving, a study by Naval Sea Systems Command revealed neither provides sufficient protection when exposed for longer times in the cold waters experienced by military divers [13]. The project was hosted by NEDU and showed neoprene wetsuits allowed an immediate and continuous drop in core body temperature over a three-hour period in water at 17–18 degrees Celsius. The dry suit was similarly tested in water at 16 degrees Celsius. While it maintained desirable heat flux levels at the skin for the first hour, the rubberized suit could not preserve core temperature over the remaining two hours such that thermal protection was significantly improved over wetsuits [13]. With few options available, individuals conducting extended operations in extremely low temperatures (e.g. during a deep salvage dive) often require active thermal insulation generated via an umbilical connection to surface supplied hot water pumped directly into the suit.



Figure 7. U.S. Navy diver in hot water suit during 2002 USS *Monitor* salvage mission. Source: [14].

This technology provides superior protection over passive systems but limits diver mobility and incurs a huge cost in equipment and man-hours to ensure surface lines do not get interrupted.

3. The Problem with Neoprene

Dive wetsuits are made of both open cell and closed cell foamed neoprene. The distinction between the two centers on whether the air pockets within the neoprene are entirely isolated from one another. Open cell foamed neoprene has gas pockets that are not entirely bound by walls, allowing the bubbles to create suction against the skin that leaves a tiny water layer between suit and skin. Closed cell foam maintains self-contained, closely packed gas bubbles that do not adhere to the skin as tightly and thus allow a greater layer of water to rest between suit and user.

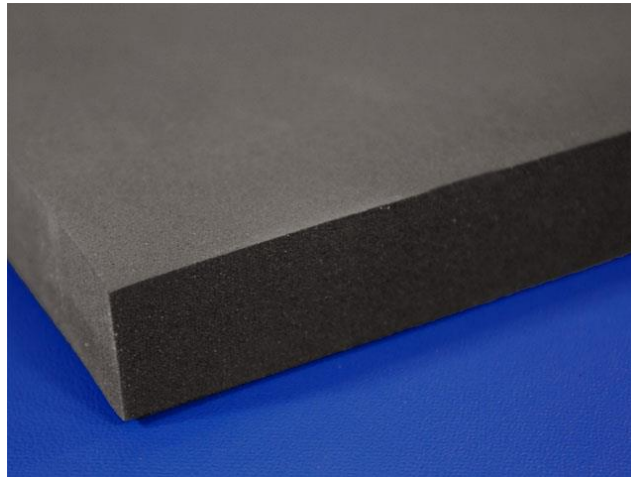


Figure 8. Closed cell neoprene foam. Source: [15].



Figure 9. Open cell neoprene foam. Source: [16].

Because of these characteristics, open cell neoprene offers greater insulation at smaller suit diameters but both types of neoprene are susceptible to the great equalizer:

pressure. When a neoprene wetsuit is subjected to increasing depth, the ambient pressure rises as well. This begins to collapse the air bubbles in the neoprene, shrinking the boundary between skin and water. The thinner barrier allows for faster heat transfer away from the skin, forcing the body to generate more heat in order to maintain its core temperature. Over sustained time intervals, the body cannot generate enough heat to match what is being lost. Therefore, it will begin to sacrifice pushing heat to extremities in order to focus on preserving necessary organ functions. If this continues, extreme discomfort such as numbness and uncontrollable shivering are followed by a sharp drop in body temperature. The diver typically surfaces prior to the onset of hypothermia but the limitations of the wetsuit have now directly limited the operation. Unfortunately, for many military dive operations, wetsuits afford the needed mobility and dexterity without the desired protection. This forces personnel to wear a bulky, cumbersome dry suit that does not afford drastic increase in submergence time [13].

4. Proposed Solution

The limitations of neoprene wetsuit performance created the impetus for a material that does not shrink appreciably with pressure. In order to prevent shrinking, a hard barrier is required to withstand the pressure without adding significant weight or bulkiness to the suit design. Historical evidence suggested the potential of glass microspheres being substituted into a polymer in order to replace the gas bubbles found in neoprene [17], [18]. Such material would maintain its original thickness under increasing ambient pressure and allow the body to warm trapped air in the material. This design was briefly pursued by the Navy Clothing and Textile Research Unit (NCTRU) but succumbed to manufacturing limitations and significant breakage of the microspheres [19]. However, modern manufacturing capabilities and drastic improvement in microsphere quality/resilience grant new applications toward diver wetsuits.

II. MATERIALS AND METHODS

A. EQUIPMENT AND CONSUMABLES

Early considerations in experimental design revolved around which pre-polymer and microsphere were appropriate for testing. The main concern with adding glass microspheres was the increased viscosity such that samples would not pour into a petri dish for thermal curing. The monomer would need low viscosity in order to combat the reduced flexibility once beads were added, as well as maintain the thermal properties needed for optimal performance. The polymer selected within these criteria was Sylgard 184 polydimethylsiloxane (PDMS), contained in 1.1 lb kits from Dow Corning through Ellsworth Adhesives, Irvine, CA. The microspheres are K1 glass microspheres from 3M manufacturing with an isostatic crush strength of 250 pounds per square inch (psi) (~8250 FSW) and a target fractional survival of 90% [20]. The resulting composites were compared to a premier wetsuit of maximum thermal protection – the 8mm Aqua Flex SolAfx from Aqua Lung. Subsequent testing of the thermal properties further dictated equipment that would subject the samples to user-regulated pressure while providing necessary values to calculate thermal insulation and resistivity.

1. Sample Fabrication

The raw PDMS is clear with relatively low viscosity comparable to maple syrup.



Figure 10. PDMS prior to being mixed with microspheres

It is poured directly into 310-milliliter THINKY mixing jars designed for the planetary rotary mixer ARE-310 by THINKY Inc., Japan. Prior to pouring the monomer and catalyst, an empty mixing jar is placed on a zeroed VWR E-series 1000g balance in order to measure how much PDMS is added. Once the two ingredients are combined, they are mixed for four minutes at 1500 rotations per minute. The glass microspheres are then dumped and mixed into the PDMS at the same speed and time interval.

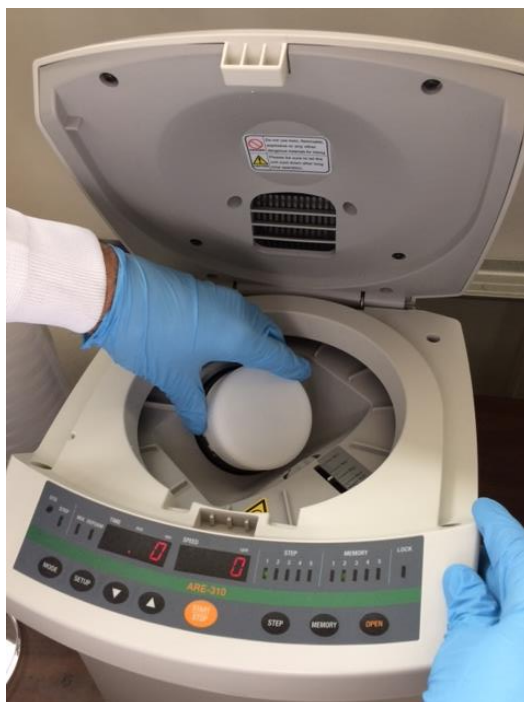


Figure 11. THINKY mixer with inserted mixing jar



Figure 12. 3M K1 glass microspheres

This step is followed by a de-foaming measure in order to rid the sample of air bubbles. The mixer has a de-foam setting which spins the jar for five minutes at 2200 rotations per minute. The resulting mixture transforms the clear polymer into a thicker, white substance that is ready to be poured into a polystyrene petri dish for thermal curing.



Figure 13. Mixed composite being poured into petri dish

The petri dish is left for at least 30 minutes at 80 degrees Celsius in a temperature-regulated oven and the resulting sample is a thermally cured disc of polymer and glass microsphere composite.

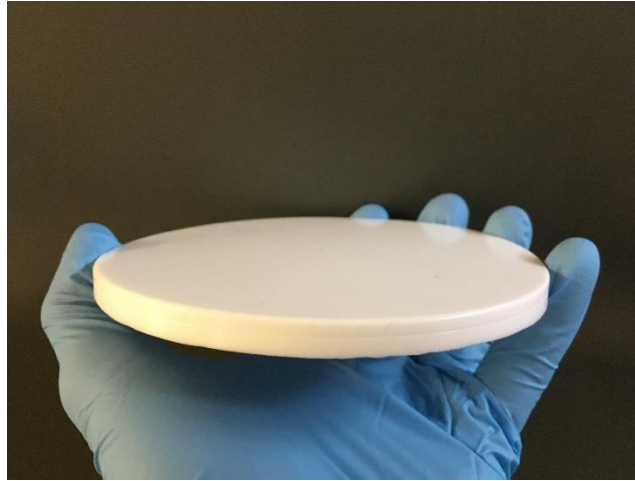


Figure 14. Fully formed sample, ready for testing

2. Experimental Setup

In order to subject the sample to comparable pressures experienced by submerged divers, a BINKS 2.8 gallon Paint Tank vessel (rated up to 80 psi) was connected to a California Air Tools Model 5510SE air compressor. The compressed air first travels to a pressure regulatory assembly where the user controls how much pressure is allowed to reach the second valve connected directly to the hatch of the vessel. A T-handle manages the second valve to control how much air is allowed into the pressure chamber itself.



Figure 15. Air Compressor attached via the pressure regulators and a hose to hanging chamber lid

Near freezing conditions are simulated by adding ice water to the fitted, pink insert inside the pressure chamber. A small, aluminum table is placed in the water so that its bottom surface and legs are submerged to serve as a heat sink. The composite is then centered on the table to imitate a wetsuit being in contact with a near-freezing environment. A circular, electronic heat plate is placed on top of the sample and receives power input from a Brooks Industries (Lake Villa, IN) heat controller, which is visible on the right side of Figure 15. Power is pumped into the heat plate to ensure it remains at human core temperature of 37 degrees Celsius.



Figure 16. Composite sample atop aluminum table and layered with heating plate.

The heat controller displays voltage and current values that are used to determine how much power is required to maintain the desired temperature. The resulting design closely imitates the human body's thermoregulatory system when exposed to low-temperature dives. The power required to keep the heater plate at 37 degrees Celsius relates to the heat being lost through the composite, which further reveals the thermal resistivity of the sample.

a. Procedure 1: Testing Sample under Pressure

The sample was subjected to incremental pressure increases of 2 to 4 psi. At each increment, the voltage and current values were given opportunity to settle for at least 2 minutes. The values were then recorded before increasing the pressure again. This process was repeated until the pressure reached 60 psi which translates to a depth of approximately 135 feet sea water (standard conversion rate: 14.7 psi approximately equals 33 FSW).

b. Procedure 2: Testing Sample at Atmospheric Pressure

The sample was tested only at atmospheric pressure by placing it in the pressure chamber but keeping the lid removed. Voltage and current values were collected 10-12 minutes after the heater plate had settled at 37 degrees Celsius.

3. Measuring Sample Dimensions

Sample diameter was set by the petri dish at 137 millimeters. Thickness measurements were taken at six evenly spaced locations using a micrometer accurate to the one hundredth of a millimeter. The resulting thickness values were averaged in order to have a single value for use in future calculations.



Figure 17. Micrometer being used to measure sample thickness

B. DESIGN CHARACTERISTICS AND CALCULATIONS

Experimental design characteristics, to include shape and size of fabricated samples, had a distinct purpose in order to mitigate undesired influences of the environment. The fabrication process achieved general sample thickness of 6-9 millimeters, mimicking the preferred suit diameters for low-temperature neoprene wetsuits. The petri dish diameter of 137 millimeters created samples that extended beyond the heater plate (diameter of 110 millimeters) in order to counteract edge effects.

1. Density and Volumetric Percentage of Microspheres

The diameter and thickness of each fabricated product was used to calculate the volume (V) using the equation for a cylinder and measured in cubic centimeters (cm^3),

$$V = \pi r^2 h, \quad (2.1)$$

where r is the radius of the sample (13.7 cm) and h is the average thickness (cm) over six different measurements. The composite's mass was then measured on the VWR E-series 1000g balance and the effective density (ρ_{eff}) was calculated in grams per cubic centimeter,

$$\rho_{\text{eff}} = \frac{m}{V} = \frac{\text{grams}}{\text{cm}^3}. \quad (2.2)$$

The volumetric percentage of microspheres within a given polymer-microsphere product (α) followed as,

$$\alpha = \frac{\rho - \rho_{\text{eff}}}{\rho - \rho_{\text{sph}}}, \quad (2.3)$$

where ρ is the density of pure PDMS (1.02 g/cm^3) and ρ_{sph} is the density of the microspheres themselves (0.125 g/cm^3).

2. Thermal Insulance

The difficulty inherent to comparing thermal insulation in neoprene and the microsphere composite is due to shrinking in neoprene under increased pressure. Therefore, the performance metric for comparing samples had to avoid any influence of sample thickness. Thermal insulance (Θ) was the appropriate parameter that met these

requirements when assessing neoprene, pure PDMS, and fabricated composites. It is defined as the ratio of the temperature difference to the heat transferred per unit time per unit area ($\frac{K * m^2}{W}$),

$$\theta = \frac{\pi D^2 \Delta T}{4 I u}, \quad (2.4)$$

where D is the diameter of the sample (137 mm), ΔT is the temperature difference between the heater and the ice water (37 degC), I is the current (amperes), and u is the voltage (volts).

3. Specific Thermal Resistivity

While neoprene suffers from pressure induced variable thickness, the composites are essentially immune to those changes. Thus, the specific thermal resistivity (R) could be used to compare thermal insulation performance between the individual composites of varying volumetric bead percentages, i.e.

$$R = \frac{\theta}{h}. \quad (2.5)$$

By dividing the insulance by h , the specific thermal resistivity is normalized for the thickness and reveals the individual material behavior of different fabricated products. This value formed the basis for the exploration of possible materials to be used in future suit prototypes.

4. Error Propagation Calculation

There was inherent error to the individual procedures for measuring required values of each variable before solving for thermal resistivity and insulance. These respective standard errors were collectively used to produce a final error for resistivity and insulance values.

a. *Uncertainty in Diameter of the Composite*

The diameter of the sample was set by the petri dish; therefore, a petri dish diameter was measured 20 times and then averaged. The standard deviation of the values was

calculated in Microsoft Excel and divided by the average diameter. The resulting value was multiplied by 4 because the standard deviation utilizes a Taylor series, which includes a squared partial derivative of the thermal resistivity with respect to the appropriate variable (in this case, diameter):

$$\sigma_f^2 = \sigma_D^2 \left(\frac{\delta R}{\delta D} \right)^2 . \quad (2.6)$$

The partial derivative of thermal resistivity with respect to diameter is

$$\frac{\delta R}{\delta D} = C * 2D , \quad (2.7)$$

where C is a set of constants. Squaring the 2D term results in a 4 being multiplied by the standard error for the diameter. The subsequent error calculated for diameter measurements was defined as

$$\sigma_D(\%) = \frac{4\sigma_D}{D_{avg}} * 100 . \quad (2.8)$$

The resulting error percentage for diameter measurements was 1.00%.

b. Thickness Measurements Uncertainty

Thickness measurements included both positional error of the measuring device itself and the variability of thickness across all samples. For positional error, a single point on one sample was measured 20 separate times. The standard deviation for this population was calculated in Microsoft Excel and divided by the average, i.e.

$$\sigma_h(\%) = \frac{\sigma_h}{h_{avg}} * 100 . \quad (2.9)$$

The error percentage for positional thickness measurements was .053%. As previously discussed, six separate thickness measurements were taken at different locations on each sample. The standard deviation percentage for each sample was then calculated in Microsoft Excel and these percentages were averaged to get a variable thickness percentile across all samples: $\sigma_{vt} = 5.37\%$.

c. Voltage, Current, and Temperature Uncertainty

Voltage, Current, and Temperature were measured from the same device. The voltage display showed to the 100th of a volt but constantly fluctuated at +/- 0.03 V. Thus,

the error was this deviation (+/- 0.03%) divided by the average of all composites' voltage values at atmospheric pressure:

$$\sigma_V(\%) = \frac{\sigma_V}{V_{avg}} * 100. \quad (2.10)$$

Voltage uncertainty calculated to $\sigma_V = 0.39\%$.

Current uncertainty resulted from occasional changes at +/-0.01 amperes, which implied that the machine used the 1000th of an ampere as the threshold for change. If the value was internally calculated to be above 0.005 A, the machine displayed the higher hundredth and if below 0.005 A, it displayed the lower hundredth of an ampere. Thus, the standard deviation is +/- 0.005 A. This deviation was divided by the average of all current values taken at atmospheric pressure in order to get the percentage uncertainty:

$$\sigma_I(\%) = \frac{\sigma_I}{I_{avg}} * 100. \quad (2.11)$$

Current uncertainty calculated to $\sigma_I = 0.72\%$.

The temperature reading would briefly move +/- 0.1 degrees Celsius, implying a threshold of 0.05 degrees Celsius in order to determine whether the higher or lower tenth would be displayed. The deviation (+/- 0.05) was divided by the temperature difference (37 degrees Celsius) to get the percentage uncertainty $\sigma_T = 0.14\%$.

d. Total Percentage Error

Total error propagation for specific thermal resistivity was calculated by taking the square root of the sum of the squares of error inherent to its variables:

$$\sigma_R(\%) = \sqrt{\sigma_D(\%)^2 + \sigma_h(\%)^2 + \sigma_{vt}(\%)^2 + \sigma_V(\%)^2 + \sigma_I(\%)^2 + \sigma_T(\%)^2} \quad (2.12)$$

Error in thermal insulance replicated equation (2.12) but did not include the errors in thickness measurements (σ_h, σ_{vt}) because the original equation for insulance (equation (2.4)) did not involve sample thickness. Final error values for resistivity and insulance were $\sigma_R(\%) = 5.52\%$ and $\sigma_\theta(\%) = 1.30\%$.

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III. EXPERIMENTAL RESULTS

A. NEOPRENE AND COMPOSITE PERFORMANCE

A total of 42 products were tested, including 39 different materials of varying volumetric bead percentages. The measured and calculated dimensions for the developed materials are presented for the record and consideration.

Table 1. Measured and calculated dimensions of all fabricated products

Sample #	Mass (g)	Thickness (mm)	Volume (cm ³)	Density (g/cm ³)	Bead Vol (%)
Pure PDMS	144.36	9.33	137.49	1.050	0.0
O1	118.50	8.53	125.80	0.942	8.7
O2	98.30	7.88	116.19	0.846	19.4
O3	94.50	7.19	105.94	0.892	14.3
O4	93.00	7.26	107.02	0.869	16.9
O5	107.00	8.50	125.29	0.854	18.5
O6	118.40	9.32	137.36	0.862	17.7
O7	88.30	7.63	112.48	0.785	26.3
O8	86.20	8.68	127.89	0.674	38.7
O9	58.00	6.49	95.71	0.606	46.3
O-10	48.00	5.93	87.43	0.549	52.6
S1	76.47	8.36	123.14	0.621	44.6
S2	73.97	8.27	121.86	0.607	46.1
S3	74.22	8.16	120.92	0.614	45.0
S4	75.80	8.34	122.85	0.617	45.0
S5	70.62	7.69	113.36	0.623	44.4
S6	75.38	7.66	112.17	0.672	38.9
S7	75.91	7.86	119.54	0.635	43.0
S8	73.61	7.87	116.10	0.634	43.1
S9	79.01	7.69	113.36	0.697	36.1
S10	77.16	8.01	118.16	0.653	41.0
S11	89.85	8.70	128.17	0.701	35.6
S12	78.31	7.50	110.61	0.708	34.9
S13	73.77	8.01	118.03	0.625	44.1
S14	91.33	8.97	132.17	0.691	36.8
S15	157.37	13.09	227.09	0.693	36.5

Sample #	Mass (g)	Thickness (mm)	Volume (cm ³)	Density (g/cm ³)	Bead Vol (%)
S16	133.72	10.99	148.91	0.898	13.2
S17	91.48	8.97	132.20	0.692	36.6
S18	109.97	10.00	147.41	0.746	30.6
S19	97.61	8.56	126.27	0.773	27.6
S20	81.71	7.49	110.42	0.740	31.3
S21	87.12	9.73	143.29	0.608	46.0
S22	70.55	8.69	128.04	0.551	52.4
S23	77.32	9.23	136.06	0.568	50.5
S24	63.22	8.05	118.70	0.533	54.5
S25	69.73	7.00	103.19	0.676	38.4
S26	70.57	7.73	113.90	0.620	44.7
S27	70.67	8.50	125.30	0.564	50.9
S28	73.01	8.00	117.93	0.619	44.8
S29	79.22	8.31	122.50	0.647	41.7
S30	57.48	6.98	102.89	0.559	51.6

Of note, the sample-numbering scheme was designed to reference samples created during certain time periods but the assembly procedure remained the same for all composites.

1. Homeostatic Behavior of Composite

In order to validate homeostasis of the composite thermal properties, the first 10 fabrications were subjected to controlled pressure increases *and* decreases while measuring associated thermal resistivity. Standard deviations among the R values ranged from 0 - 3.9% while surviving controlled pressure changes from 0-60 psi and from 60-0 psi. This effort proved that the materials were not being compromised by the stress of drastic pressure differences.

Table 2. Standard deviations of thermal resistivity values for ascending and descending pressures ranging between 0 and 60 psi

Sample #	Bead Vol(%)	R Std Dev % (0-60psi)	R Std Dev % (60-0psi)
O1	8.7	1.1	0.5
O2	19.4	1.2	3.9
O3	14.3	1.4	0.7
O4	16.9	0.9	0.0
O5	18.5	1.4	0.7
O6	17.7	2.8	1.5
O7	26.3	1.4	1.1
O8	38.7	1.5	3.1
O9	46.3	1.3	1.0
O10	52.6	1.5	0.3

2. Thermal Insulance: Neoprene versus Composite

Comparing the thermal insulation performance of the 8mm wetsuit sample and a composite with 43% bead volume reveals drastic differences in tolerance to pressure.

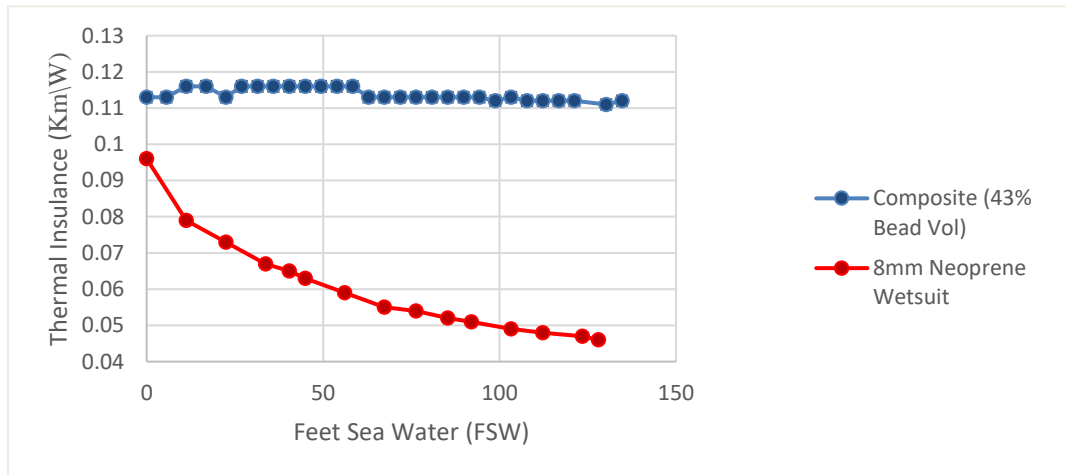


Figure 18. Comparison of thermal insulation behavior between neoprene and composite with increasing depth (error bars are of equal size to points on graph)

Neoprene suffers a steady decline in thermal insulance totaling 52% difference between its highest and lowest values over a range of 0 to 128 FSW. Conversely, the selected composite incurs a 4.3% difference between its extremums over a range of 0 to 135 FSW. Furthermore, at 128 FSW, the fabricated sample demonstrates a 59% higher value for thermal insulance over neoprene. Similar precision is observed in the thermal insulance for all 14 materials subjected to pressure differential testing.

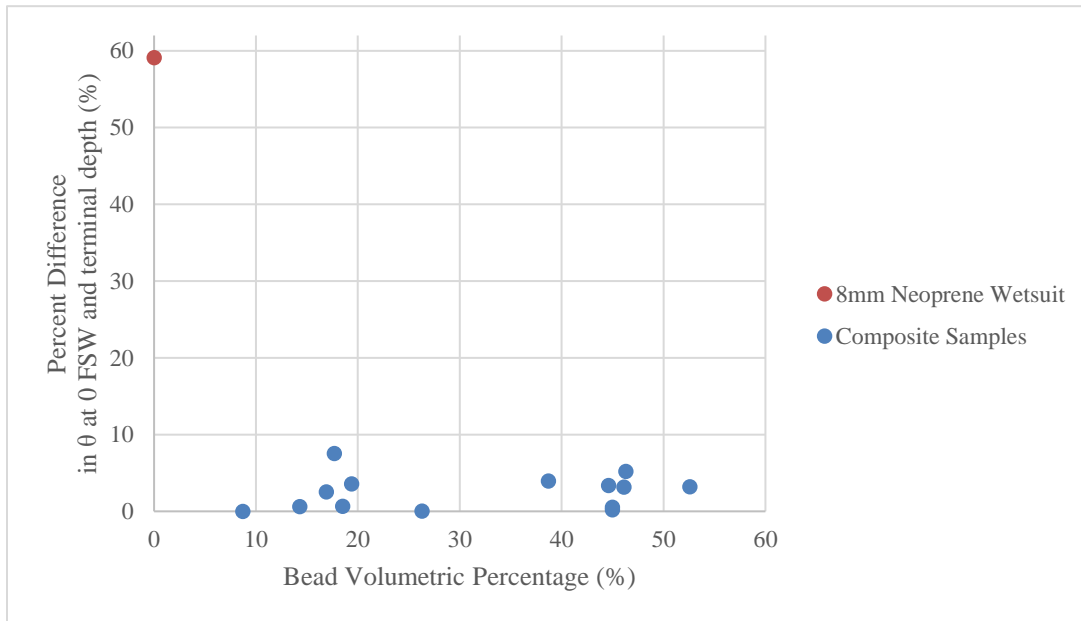


Figure 19. Percent difference in θ values at 0 FSW and terminal depth (128-135 FSW)

While varying bead volumetric percentages adjusted the performance of the materials, neoprene demonstrates a severe departure from the small variations in thermal insulance expressed by the composites. These data established a critical thermal property of the composite by demonstrating that there is no appreciable degradation in thermal insulance regardless of bead volumetric percentages or increases in depth. Thus, the remaining 27 samples were tested for specific thermal resistivity at atmospheric pressure (0 FSW), avoiding the need for pressure testing and accelerating the research and development process.

B. SPECIFIC THERMAL RESISTIVITY AMONG SAMPLES

Variations in bead volumetric percentages were expected to have significant influence on the specific thermal resistivity of each fabricated material. Testing all materials at atmospheric pressure and determining their associated R values produced necessary data to reveal the connection between bead density and heat retention.

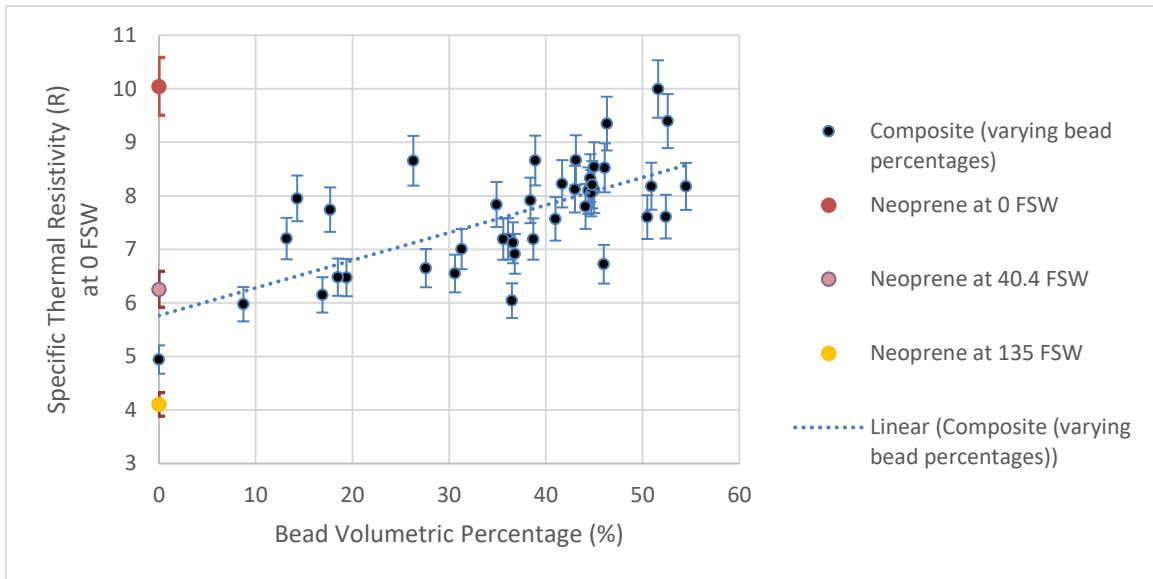


Figure 20. Material specific thermal resistivity at 0 FSW as a function of microsphere volumetric percentage

The trendline reveals a linear increase in thermal resistance with a concurrent rise in bead density and allows adjustable thermal protection based on need. Neoprene performance is plotted along the y-axis at three separate depths to reveal the severe degradation of thermal protection as the diver descends underwater. The draft limit of the USS *Gerald R. Ford* is listed at 41 FSW where navy divers conduct prolonged, submerged ship maintenance [21]. At a comparable depth of 40.4 FSW, neoprene has lost 38% in thermal resistivity and shows an R value below 92.5% of all composites. Various outliers with high bead density composites but lower specific thermal resistivity are most likely due to uneven distribution of the microspheres such that heat passes through some samples more easily than others.

Furthermore, neoprene is limited in thickness in order to preserve its flexibility for a tight fit on the human body. Commercial suits do not exceed 8mm, which further limits achievable thermal protection. However, the fabricated materials are designed for segmented fitting in which the body is covered by contoured plates. This allows greater range of thickness to cover the largest surface areas of the body while keeping the joints covered by small patches of flexible material to maintain maximum range of motion. Thus, future materials could be created at 16mm thickness to double thermal protection at water's surface and concurrently have thermal insulation four times better than neoprene at depth.

IV. DISCUSSION

A. COMPOSITE CHARACTERISTICS

The fabricated materials directly address the critical flaw of neoprene by sustaining the necessary boundary for proper heat retention at increasing depths. The unique properties of modern glass microspheres make them a powerful control point for varying levels of passive thermal protection. Data reveals that increased bead density directly translates to higher thermal protection; combining the upward trend of data in Figure 20 with future increases in sample thickness projects even larger values in thermal resistivity. Thus, while the modern neoprene wetsuit has seemingly peaked in its performance characteristics, the composite gives continued promise for upward mobility in thermal insulation.

1. Composite Ingredients

The unique resilience of the glass microspheres allows for a simple, efficient fabrication process. Despite being packed aggressively into the polymer and subjected to large variations in pressure, the hollow beads show no significant breakage or degraded thermal properties. Ultimately, the negligible weight and high isostatic crush strength of the hollow beads preclude them from limiting the diver's achievable depths and extend the performance of the composite.

The microspheres and polymer are low-cost and safe to handle. Neither ingredient is caustic to human skin and the 3M glass bubbles can be both inhaled and in contact with human eyes with little adverse effect [22]. In addition, both are biologically and chemically inert and non-toxic to the natural environment. Conversely, neoprene requires expensive, high-precision equipment in order to control the input of gas to create the required foamed effect and is further limited by the availability and cost of those gases.

2. Buoyancy

At the water's surface, neoprene's air bubbles are lighter than water and help the diver stay afloat. However, the descent underwater collapses the air boundary and quickly

induces a greater loss in diver buoyancy. Divers are subsequently forced to make large-scale adjustments on buoyancy control devices (BCD) as they descend. Fortunately, the composites' structure directly counteracts this failure through the air trapped in the hollow microsphere. This hardened air boundary translates to the diver experiencing sustained buoyancy throughout the dive such that less time would be required to manipulate the BCD. By minimizing attention on the BCD, the diver can apply more of his limited air supply to tasks related directly to mission accomplishment.

3. Limitations and Possible Solutions

The composite shows weakness in one notable area: flexibility. Increasing the density of glass microspheres directly limits the flexibility of the resulting material. The tested neoprene sample can be rolled multiple times into a small spiral, highlighting its natural quality to contour with the human form. A composite sample with 26.3% bead density resists even being folded in half.



Figure 21. “Fold test” of neoprene sample and fabricated composite

A first solution to this issue is changing the carrier polymer in favor of one that is potentially more flexible after thermal curing. There are a myriad of different ingredients that might be combined to restore flexibility based on individual material properties and how they each respond to the fabrication process. The second proposed solution relates to

original intent for suit design. The current composite will be used to make a suit that is segmented and molded to fit various body types. In effect, the composite would be formed like pieces of armor and contained in a durable outer fabric similar to the housing material for foamed neoprene. Using 3D manufacturing, the composite pieces can be designed to cover parts of the body where heat loss is greatest and allow for current materials to be used in human testing. The 3D printing process, by either thermal extrusion or optical curing stereolithography, does not exceed costs associated with neoprene fabrication even as the technology becomes cheaper through improved efficiency and availability. Thus, the compatibility of the new material and 3D printing allows for continued composite use amidst advancements in manufacturing design.

B. FUTURE RESEARCH

Exploring passive thermal protection for low temperature environments grants future military divers with a dramatic increase in operational mobility. Glass bubbles and polymer provide a wide range of possible combinations that could drastically improve different facets of composite performance. Various carrier polymers and brands of microsphere should be tested for their influence on material flexibility and higher degrees of predictability in thermal protection. Outlying data points in Figure 20 most likely reflect non-uniform distribution of the beads, leaving channels that facilitate unwanted heat transfer. This problem may be mitigated through different brands of ingredients and an additional control factor during the fabrication process to improve even spreading of the glass bubbles. Additionally, mixing heterogeneously sized microspheres may improve packing arrangements and minimize unwanted thermal passageways.

Advancements in 3D printing make suit prototypes an immediate reality. Human test subjects can receive full-body scans from which a tailored composite suit may be built for the individual. Ideally, as much of the body should be covered by the composite because the human body loses the most heat through the largest surface area exposed to the environment [23]. Thus, the composite should seek to cover as much of the body as possible and leave only the joints available for necessary range of motion. Another possible suit design includes layering very thin sheets of composite (similar to a small stack of

paper) within a holding material. This would potentially improve flexibility and allow for overlapping layers of beads to improve overall microsphere distribution.

While the composite has not been tested for its response to shock pressure or high-speed impact, there may be potential for ballistics testing. The integration of both hollow and solid ceramic microspheres into the polymer could limit the penetration of certain caliber rounds. A current U.S. Patent application is founded on a flexible body armor that includes “a flexible liner, a polymer binder disposed on the liner, and ceramic solids embedded in the binder” [24]. This effort might focus on creating a small-caliber resistant material that is selectively placed into the suit to cover body parts that house critical arteries or organs.

V. CONCLUSION

A composite material of 3M K1 glass microspheres and Sylgard 184 polydimethylsiloxane has been proven to show superior values in thermal insulation compared to a sample of 8mm foamed neoprene wetsuit when exposed to descending and ascending pressures. By submitting each sample to the stresses of common operating environments facing U.S. military divers, it was determined that neoprene lost 59% of its thermal resistivity while the composite sample showed deviations not exceeding 3.9%. At 135 FSW, fabricated materials displayed thermal resistivity values as high as 58.9% higher than neoprene.

Amidst successes, the composite maintains a flexibility deficiency. The long-term solution is finding both a superior polymer and microsphere that improve material malleability and assess any negative contributions during the fabrication process. Desirable qualities of future ingredients might include lower viscosity in the polymer and lubricated glass bubbles in order to reduce friction during bending. Another approach is tailored segmentation, which adds both complexity and creativity via 3D printing capabilities, and produces the maximum variability of thermal protection solutions.

The breadth of military dive operations demands further exploration of this technology in order to extend the operational capability of the U.S. military dive force. U.S. military dive history is rife with brave men and women who pushed the boundaries of technology in order to support an expanding set of underwater missions. Extending U.S. capabilities to operate in littorals worldwide will serve as the key to future strategic successes.



Figure 22. U.S. Navy SEALs emerging from a subsurface insertion.
Source: [25].

Such capabilities will forever include dive operations in which the nation can maintain access to environments that are otherwise contested or opposed. Just as aircraft technology redefined warfare, the subsurface environment represents a vast, underused point of access to further U.S. interests abroad. In order to make this a reality, tactical equipment must mitigate the influences of austere environments in which U.S. divers often conduct their influential work. Let this effort be the beginning of new technologies that support the warfighters who rely on such research to protect their lives in real-world missions.

LIST OF REFERENCES

- [1] Naval Sea Systems Command, *U.S. Navy Diving Manual*, 7th ed., vol. 1. Washington, DC: Naval Sea Systems Command, 2016. [Online]. Available: http://www.navsea.navy.mil/Portals/103/Documents/SUPSALV/Diving/US%20DIVING%20MANUAL_REV7.pdf?ver=2017-01-11-102354-393
- [2] J. Macdonald, "From reeds to regulators: The history of scuba," *Scuba Diver Life*, Jan. 21, 2016. [Online]. Available: <https://scubadiverlife.com/reeds-regulators-history-scuba/>
- [3] United Nations Department of Economic and Social Affairs, "Percentage of total population living in coastal areas," Center for International Earth Science Information Network at Columbia University (CIESIN), Palisades, NY, USA, 2010. [Online]. Available: http://www.un.org/esa/sustdev/natlinfo/indicators/methodology_sheets/oceans_seas_coasts/pop_coastal_areas.pdf
- [4] M. Hixenbaugh, "Silent threat: Are sea mines the Navy's Achilles' heel?" *Virginian-Pilot*, Nov. 11, 2015. [Online]. Available: https://pilotonline.com/news/military/article_b61595e0-33e5-59cb-a626-c125049f34d3.html/
- [5] Subsea Worldnews Staff, "USA: Navy uses new underwater support model for ship hull inspections," *Subsea World News*, April 27, 2012. [Online]. Available: <https://subseaworldnews.com/2012/04/27/usa-navy-uses-new-underwater-support-model-for-ship-hull-inspections/>
- [6] "Diving in the U.S. Navy: A brief history," Naval History and Heritage Command, Jul. 2017. [Online]. Available: <https://www.history.navy.mil/research/library/online-reading-room/title-list-alphabetically/d/diving-in-the-u-s-navy-a-brief-history.html/>
- [7] USNUM Curator, "MK V diving rig," U. S. Naval Undersea Museum, Sep. 19, 2016 [Online]. Available: <http://www.navalunderseamuseum.org/mk-v/>. [Accessed: 30-Apr-2018].
- [8] D. Huitt, "Watch: 20,000 dive hours spent salvaging the sunken ships of Pearl Harbor," *SOFREP*, Dec. 9, 2016. [Online]. Available: <https://sofrep.com/69519/watch-20000-dive-hours-spent-salvaging-sunken-ships-pearl-harbor/>

- [9] M. Scichilone, "U.S. Navy photo archive," U.S. Navy Official Site, Feb. 13, 2014. [Online]. Available: [http://www.navy.mil/gallery_search_results.asp?terms=navy diving center&page=6&r=4/](http://www.navy.mil/gallery_search_results.asp?terms=navy+diving+center&page=6&r=4/)
- [10] "Hypothermia," Mayo Clinic, Jan. 6, 2018. [Online]. Available: <https://www.mayoclinic.org/diseases-conditions/hypothermia/symptoms-causes/syc-20352682/>
- [11] H. Ornhagen, "Thermal problems in diving," Lecture in Tokyo, Japan, Nov. 4, 2004. [Online]. Available: <http://www.ornhagen.se/Thermal%20problems%20in%20diving%20050106%20Hemsida.pdf>
- [12] B. Stanley, "U.S. Navy photo archive," U.S. Navy Official Site, Mar. 14, 2017 [Online]. Available: http://www.navy.mil/gallery_search_results.asp?terms=ice+diving&page=3&r=4
- [13] J. C. Mollendorf and D. R. Pendergast, "Thermal protection system for underwater use in cold and hot water," *Journal of Thermal Science and Engineering Applications*, vol. 2, no. 1, pp. 011003–2, Mar. 2010. [Online]. Available: <https://static1.squarespace.com/static/5911c931c534a5947d59d871/t/598dda97ebbd1ae72c809180/1502468761283/DM2010.pdf/>
- [14] "The skin they're in: U.S. Navy diving suits," U. S. Naval Undersea Museum. Accessed April 30, 2018. [Online]. Available: <https://www.history.navy.mil/museums/keyport/SkinThey'reIn/skin4.htm/>
- [15] "Closed cell neoprene sponge rubber," The Rubber Company, 2018. [Online]. Available: <http://therubbercompany.com/products/closed-cell-neoprene-sponge-rubber/>
- [16] "Open cell neoprene sponge sheets," Equal Seal, 2018. [Online]. Available: <https://www.equalseal.com/product-p/neosp-oc-1251836psa-.htm/>
- [17] F. Dawans "Polybutadiene compositions containing reinforcing glass microspheres and carbon fibers," U.S. Patent 4107134, Aug. 15, 1978. [Online]. Available: <https://patentimages.storage.googleapis.com/31/a5/4a/6753598ba80887/US4107134.pdf/>
- [18] W.S. Friedlander and N. Jones, "Deep submergence diving suit and insulative material therefor," U.S. Patent 3660849, May 9, 1972. [Online]. Available: <https://patentimages.storage.googleapis.com/e8/c6/9d/0373a8ef956b43/US3660849.pdf>

- [19] N.F. Audet and M.N. Larrivee, "Development and evaluation of deep-sea swimsuit materials," NCTRU, Natick, MA, USA, Rep. ADA306253, Jun. 1973. [Online]. Available: <http://archive.rubicon-foundation.org/xmlui/bitstream/handle/123456789/5019/ADA306253.pdf?sequence=1/>
- [20] 3M Manufacturing, *3M Glass Bubbles Product Information*, 98-0212-3859-1, 2013. [Online]. Available: <http://multimedia.3m.com/mws/media/910490/3m-glass-bubbles-k-s-and-im-series.pdf>
- [21] "USS *Gerald R. Ford* (CVN 78)," *Naval Vessel Register*, Jul. 25, 2017 [Online]. Available: http://www.nvr.navy.mil/SHIPDETAILS/SHIPSDETAIL_CVN_78_4524.HTML/
- [22] 3M Manufacturing, *3M Glass Bubbles material safety data sheet*, 10-4852-9, Feb. 15, 2018. [Online]. Available: https://multimedia.3m.com/mws/mediawebserver?mwsId=SSSSSuUn_zu8l00x4xtZ58_vPv70k17zHvu9lxtD7SSSSSS--/
- [23] A. O'Connor, "The claim: You lose most of your body heat through your head," *New York Times*, Oct. 26, 2004. [Online]. Available: <https://www.nytimes.com/2004/10/26/health/the-claim-you-lose-most-of-your-body-heat-through-your-head.html>
- [24] C. M. Roland and R. M. Gamache, "Body armor of ceramic ball embedded polymer," U.S. Patent 2012/0312150 A1, Dec. 13, 2012. [Online]. Available: <https://patentimages.storage.googleapis.com/4c/81/94/54edd9b5e2232b/US20120312150A1.pdf>
- [25] D. B. Larter and M. Myers, "Navy SEALs set to open to women, top admiral says," *Navy Times*, Aug. 18, 2015. [Online]. Available: <https://www.navytimes.com/news/your-navy/2015/08/18/navy-seals-set-to-open-to-women-top-admiral-says/>

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