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14. ABSTRACT

US Naval Special Operations Forces increasingly operate in the frigid waters of the arctic. Of particular concern is the loss of dexterity and numbness in the hands during dives. JHU/APL's Polar Grip is a tactical dry glove designed to keep hands warm and dry under such conditions. The glove uses three thin layers to improve warmth without adding bulk.

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JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Please refer to:
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21-Nov-19

Dr. Reginald A. Beach
Office of Naval Research
Code 322
875 North Randolph Street
Arlington, VA 22203-1995

Dear Dr. Beach:

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) is pleased to submit the enclosed Final Technical Report for the "Polar Grip Phase IV: Tactical Dry Glove for Polar Environments" project, APL Task FGD14, for September 1, 2018 to February 28, 2019.

If you have any questions or comments regarding this report, please free to contact me at 240-228-7309 or email Michael.Jin@jhuapl.edu.

Sincerely,

Original signed by,

Michael Jin
Project Manager

Polar Grip Phase IV: Tactical Dry Glove for Polar Environments
Final Technical Report

Award No. N00014-18-1-2748

Submitted by,
The Johns Hopkins University Applied Physics Laboratory
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Office of Naval Research, Code 322

From: Dr. Michael Jin, Project Manager

Reporting Period: September 1, 2018 to February 28, 2019

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TABLE OF CONTENTS

1. Summary

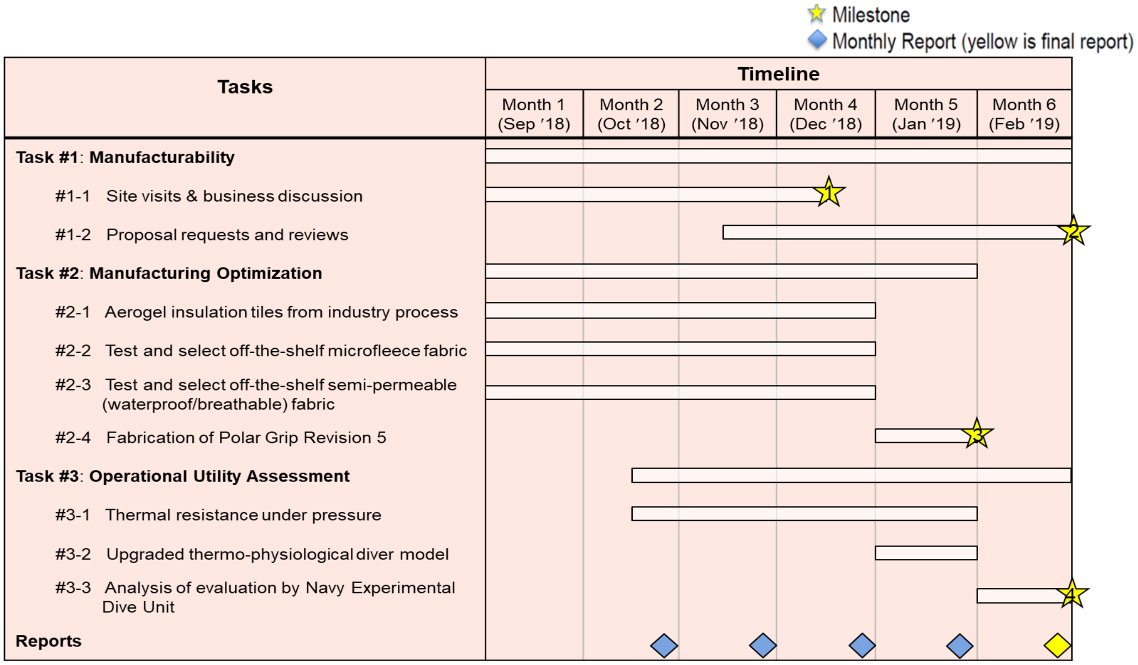
- **<u>Industry partner for collaboration has been identified</u>**: Aqua Lung has been identified as the leading candidate as an industry collaborator for future tech transfer effort. Aqua Lung has submitted a planning letter to JHU/APL detailing their approach. JHU/APL is also continuing dialogue with two additional companies (Henderson Sport Group, and Dive Right in Scuba) who do not desire R&D collaboration, but are willing to provide services in fabricating gloves.

- **<u>Fabrication and performance of Polar Grip Revision 5</u>**: The manufacturability of Polar Grip has been improved by fabricating a new prototype glove using all commercially available materials including Airloy® X116 aerogel, eVent® waterproof breathable fabric, and white fleece fabrics from Jo-Ann. Polar Grip Revision 5 performs 28% better than the control for dry skin in air and 3× better for sweating skin, both in air and cold water. Further improvement in glove design and fabrication is necessary in the next phase to optimize its performance in water.

- **<u>Operational utility assessment</u>**: New data on the thermal resistance of thermal insulators under hydrostatic pressure in water has provided direct evidence that the resistance of aerogel changes little down to the water depth of 100ft, and Polar Grip can provides very efficient thermal protection in pressurized water. The test at Navy Experimental Dive Unit (NEDU) has been strategically delayed in order to make further improvement in form, fit, and function (FFF). NEDU will be re-engaged after optimizing FFF with Aqua Lung in the next phase.

2. Project Goals and Objectives

Phase IV of Polar Grip (6-month effort) was devoted to enabling a rapid and smooth tech transfer effort in the next phase. Phase III culminated in the production of a five-finger glove prototype (Revision 4), which allowed full movement of the hand. Thermal resistance during sweating was also improved due to the use of a less water absorbent semipermeable layer, which minimizes thermal conduction since less water is absorbed. The technical effort in Phase IV was focused on identifying and developing materials and process solutions that ease the tech transfer transition, and on collecting thermal resistance data under pressure that can quantitatively assess the operational utility of Polar Grip. The diagram below provides a more detailed view of Phase IV project tasks, subtasks, schedule and milestones. In the future Transition Phase I, JHU/APL and the industry partner will develop an industry-version of the Polar Grip prototype, with an ultimate goal of making a commercial Polar Grip available to the U.S. Navy and other services at the end of Transition Phase II.



Milestone 1: Site Visits Completion
Milestone 2: Manufacturer Selection
Milestone 3: Polar Grip Revision 5 Completion
Milestone 4: Operational Utility Assessment Completion

3. Key Accomplishments

3.1 Manufacturability (Task #1) - Industry Engagement

Early in this phase, JHU/APL identified three potential industry collaborators including Aqua Lung America, Henderson Sport Group, and Dive Right in Scuba (DRiS). After visiting all candidates, we have identified Aqua Lung as the leading candidate for the partnership because Aqua Lung has a dry suit business, the expertise necessary for the technical work and is most familiar with how a typical collaborative R&D project works. Most importantly, Aqua Lung showed strong commitment for the collaboration by visiting JHU/APL, engaging us for discussions, and responding to the request for planning letter issued by JHU/APL in January – the other two companies did not respond. The letter received from Aqua Lung detailed their proposed approach and the cost necessary for the work, which we determined is adequate for the future work.

With a non-disclosure agreement in place for all three companies, JHU/APL shared the previously fabricated Polar Grip prototype and explained the three main features of Polar Grip, which provided the basic understanding of Polar Grip to them. Purposely, JHU/APL did not share the thermal performance data of Polar Grip with any company, including Aqua Lung. This data will be shared with the collaborators when the actual transition phase begins. At this time the best approach for collaboration will be determined.

While Henderson and DRiS do not desire to work under a formal R&D collaboration setting, they are still interested in working on Polar Grip. Henderson currently does not have a dry suit business and is only interested in improving the aerogel insulation liner, making it compatible to most major dry suit systems available in the market, and potentially commercializing it for users. DRiS, primarily known as a retail store to the dive community, runs a technical shop for repairs and alterations of diving equipment. DRiS is interested in improving Polar Grip by assisting JHU/APL with glove fabrication, with an ultimate goal of making Polar Grip available for Navy users and others. In fact, DRiS assisted JHU/APL in the current phase by fabricating the Polar Grip, which gave them a chance to sew aerogel and other components into gloves. More information on these three companies can be found in Polar Grip Phase IV Progress Report #2 submitted on January 2, 2019.

3.2 Manufacturing Optimization (Task #2)

3.2.1 Polar Grip Revision 5: Design and Thermal Performance

The fifth revision of the Polar Grip prototype was completed. The new design is summarized in Fig. 1, which depicts the following changes from the fourth revision:

- Replaced laboratory-made materials with commercially available fabrics to ease tech transition – replaced semipermeable layer with waterproof breathable eVent® fabric, and replaced chopped polypropylene fibers (fleece) with white fleece fabrics from Jo-Ann.
- Replaced Airloy® X103-M aerogel with Airloy® X116, which enabled simple molding and casting of the tiled aerogel arrays – X116 is planned for mass production by Aerogel Technologies, LLC.
- Separated fleece from the rubber glove and made an optional fleece glove that can be worn on top of the rubber glove – the fleece only provides extra physical protection in water without any thermal benefit.
- Added the waterproof breathable eVent® fabric to cover up the sticky aerogel backing layer made of polyisobutylene (PIB)-coated elastic fabric.

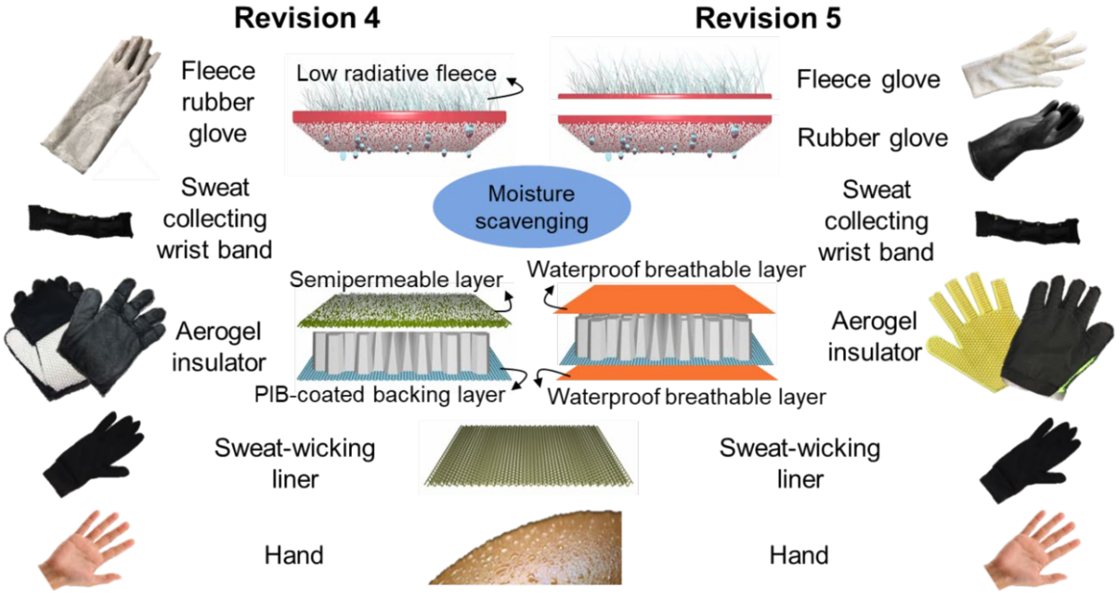


Figure 1. Schematic of the Polar Grip Revision 5 and its comparison to the Revision 4. The manufacturability of the Polar Grip is improved by avoiding precision machining and by replacing laboratory-scale custom-made fabrics and fleece with commercially available materials.

Thermal performance of the gloves presented in Fig. 2a indicates that the new Polar Grip prototype, overall, performed 28% and 78% better than the control, respectively, for dry and sweating skin in air. The performance can be attributed to a combination of the glove constituent technologies, including not only aerogel but also fleece. It can be seen that the thermal resistance of the Polar Grip glove without the fleece was lower than the resistance of the control. New to Revision 5, the Airloy® X116 aerogel tiles were fabricated using a molding and casting process. In future studies it is necessary to ensure that the thermal resistance of the fine-featured tiles is fully preserved during the molding and casting process. Relative to the control, Polar Grip is more tolerant to sweating skin condition in air. The addition of sweat resulted in a resistance decrease of 17% for Polar Grip, while the control lost 40% of its thermal resistance.

As shown in Fig. 2a, the thermal resistance from any glove decreases when immersed in water at 2 °C. When the gloves were tested for dry skin in the 2 °C water, the resistance decreased 54% and 67%, respectively, for the control and Polar Grip. Measurements of the thermal performance of the gloves immersed in cold water indicated there are multiple elements working together. These factors include the reduced temperature, the hydrostatic pressure compressing the glove, and the tight thermal interface between the glove and the heat conducting medium (water). Assuming no change in thermal resistivity, the decrease in thermal resistance should be explained by the decrease in thickness of the glove under water and presence of any thermal defects. Under these cold water test conditions, any small thermal defects resulting from non-optimized glove design and fabrication resulted in significant performance reductions on measurement. Further study is necessary to confirm the correlation between resistance and thickness reduction, and also to examine the thermal design and the defects for both gloves. The benefit of Polar Grip against sweating is shown again in Fig 2a with only a 12% decrease in thermal resistance with sweating compared to the dry skin case. Compared to the control, Polar Grip is 3× more tolerant of sweating in both air and water.

In order to gauge the effect of water temperature on the thermal 'resistivity' of the glove independent of other factors, the thermal resistance of the glove was collected in water thermally equilibrated with atmosphere at 22 °C prior to the test (Fig. 2b). The thermal resistance was higher in the colder water for both the control and the Polar Grip, indicating that thermal 'resistivity' of the glove was also higher in the colder water for both gloves.

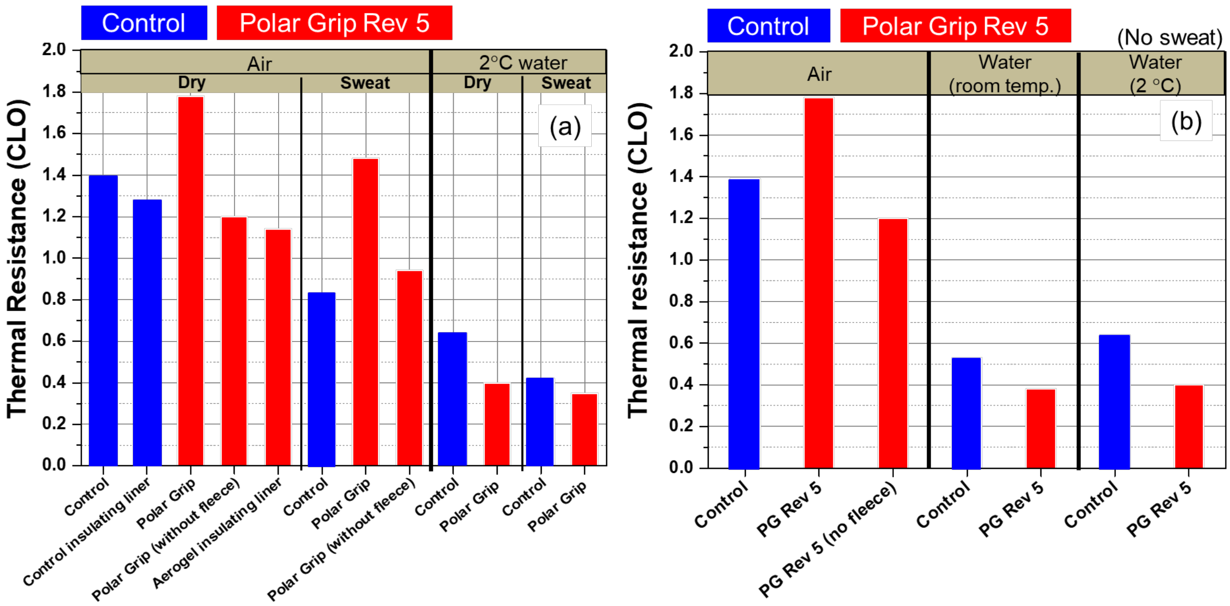


Figure 2. Thermal resistance of the control glove and the Polar Grip Revision 5 in air or water: (a) tested under both dry and sweating skin conditions and water at 2 °C, (b) tested under dry skin condition with water at room temperature or 2 °C.

Another potential benefit of Polar Grip is its performance underwater at depth because the aerogel is incompressible (compressive modulus of 1,595 psi from vendor specification) compared to the fiber-based insulator used in the control. Thermal resistance data presented in Fig. 3 clearly show this benefit. The aerogel coupon showed little change in its thermal resistance up to 54 psi, a pressure compatible to the 100 ft water depth targeted for Polar Grip. This agrees with the high compressive modulus of the aerogel because 54 psi would generate only ~3% strain, and thus ~3% decrease in thermal resistance, which was not significant enough to be seen in this experiment. On the other hand, the thermal resistance of the fiber-based insulation from the control decreased by ~68% when the pressure was increased from 14 psi to 54 psi and it was attributed to the change in the thickness of the fiber-based insulator. Future effort should include tests in air and in cold water in order to understand the effect of water and its temperature on the thermal resistance at the material level.

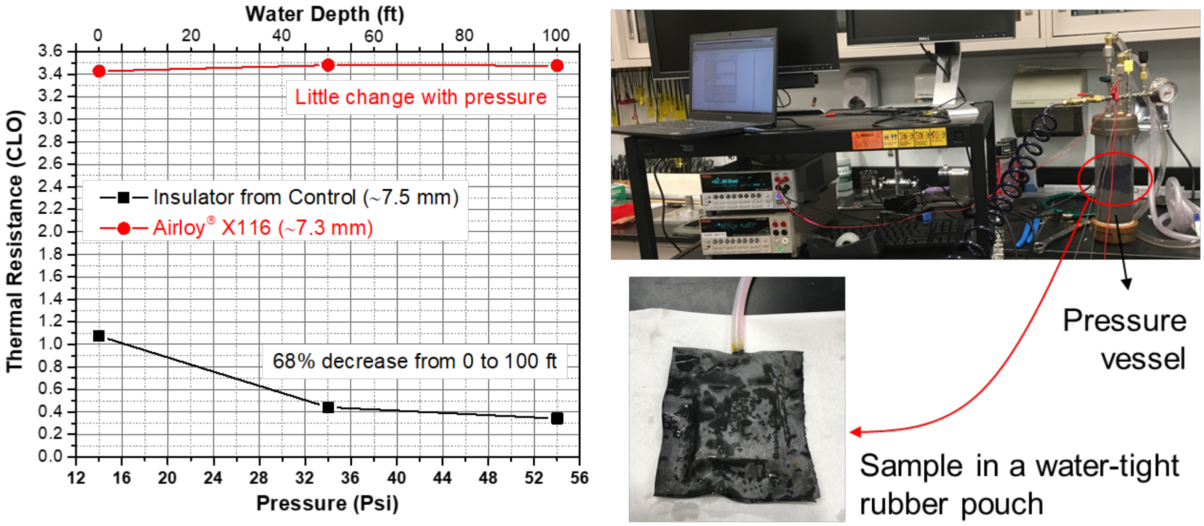


Figure 3. Thermal resistance of insulating materials (16 cm^2 size coupons) characterized in a pressure water vessel built in this phase – the set-up was rated for a pressure compatible to the 100 ft water depth targeted for Polar Grip. The water was at room temperature and pressurized by air introduced into the vessel in order to realize targeted hydrostatic pressure. It was assumed that the coupons experienced 14 psi of atmospheric pressure when there was no air pressure applied.

Another set of efforts made in parallel to calculate thermal 'resistivity' of Airloy® X116 as a function of a compressive stress was unsuccessful. As described in Progress Report #1, an existing vacuum test station was modified to apply stress and measure the thermal resistance and the thickness of the sample at the same time. A series of preliminary tests, however, revealed that the level of parasitic heat conduction present under 15 mtorr of vacuum was not small enough to achieve necessary sensitivity to characterize the heat flow through ~2mm thick aerogel material. Achieving the necessary sensitivity requires the amount of heat flow through the sample to be much more significant compared to the parasitic heat flow. The best way to achieve the necessary sensitivity under the given resources was to thin down the material further, which also complicated the thickness measurement. Since data from Fig. 3 indicated there was potentially insignificant change in the thermal resistivity under the range of hydrostatic pressure relevant to Polar Grip, no further effort was made and is planned either for future.

3.2.2 Polar Grip Revision 5: Materials and Fabrication

In this phase, materials and the glove components necessary for the fabrication of Polar Grip Revision 5 were selected, tested, and prepared by JHU/APL. DRiS provided a Cut & Sew service to fabricate gloves (Fig. 4). During the fabrication, DRiS added fourchettes between fingers to ease the insertion of the hand into the aerogel insulation glove (Fig. 4d), but the current prototype does not have aerogel underneath the fourchettes, resulting in thermal defects. The thermal resistance in air was 33% higher at the palm of the glove than at the other areas combined. The design and fabrication need to be optimized going forward to ensure thermal defects are minimized wherever possible.

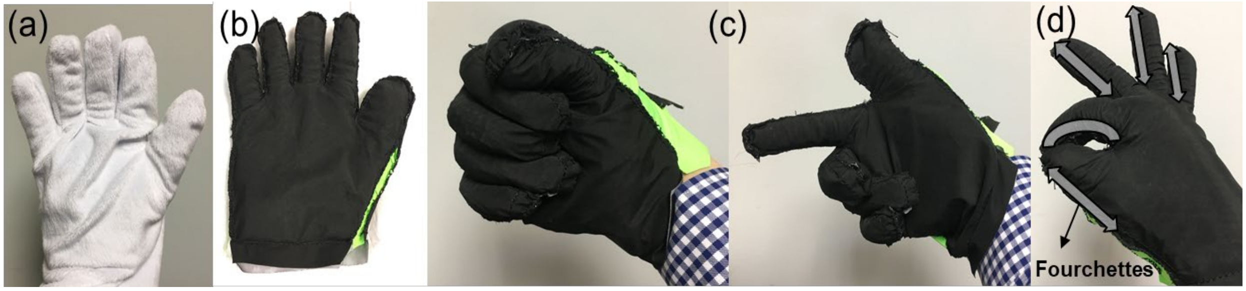


Figure 4. (a) Completed Polar Grip Revision 5 with the fleece glove on, (b) completed aerogel insulation liner, (c) full finger movement in the aerogel insulation liner, and (d) fourchettes added to ease the insertion of fingers into the liner. The width of the fourchettes is about 1 cm.

While the Polar Grip exhibits a strong advantage in sweating conditions, it should be noted that sweat still reached the aerogel layer through seams in the new prototype. Further effort in thermal design and glove fabrication will be sought from industry in the future tech transfer phase. Potential solutions include applying water-tight sealant.

3.2.2.1 Aerogels

Two different approaches were taken in this phase to improve the manufacturability of the aerogel tiles by avoiding the precision machining used previously. The approaches included Molding & Casting and Machine Slitting. The Molding & Casting process was very successful as all of the fine features of the tiles were retained in the final products after being cast off the silicone mold (Fig. 5a). The mold was oversized to compensate for shrinkage during the drying process, which was done by either supercritical CO_2 drying (2-3 days) or ambient drying (2-3 weeks), with the linear shrinkage of 7.5 % and 12 %, respectively. The vendor (Aerogel Technologies LLC) prefers ambient drying because it is less expensive and produces aerogels of slightly higher quality. Any future Molding & Casting process should minimize the excess blank aerogel material backing the tiles in order to avoid a polishing step that was necessary to thin down the tiles after casting. The polishing step generated defects in the tiles and broke the tiles into smaller pieces, which could lower the thermal performance of the glove (Fig. 5b). Machine Slitting was also very effective in fabricating the tiles, but unintended oil drips on the aerogel during the process densified and deformed the material (Fig. 5c). A similar issue was discovered when the aerogel tiles were glued to its backing layer, a PIB-coated elastic fabric using chlorobenzene. The organic solvent applied to the aerogel densified the material and deformed the tiles (Fig. 5b). While we have minimized this issue during the fabrication process through engineering solutions, a more consistent and scalable approach is necessary to avoid the risk of ruining the aerogel during processing or when exposed to sweat during operation. A potential solution is to apply a protective coating on the tiles. Fig. 5d shows the particular set of aerogel tiles used in the Polar Grip Revision 5 – Molding & Casting followed by ambient drying and polishing steps was employed and the completed titles were glued to the PIB-coated elastic fabric.

Figure 5. Aerogel tiles made of Airloy® X116: (a) a set of tiles fabricated by Molding & Casting and supercritical CO_2 drying process, (b) a set of tiles from (a) glued to the elastic backing fabric showing various defects caused by polishing and gluing, (c) a set of tiles fabricated by Machine Slitting – the area damaged by oil drips is indicated by a red circle, and (d) a pair of tiles ready for the fabrication of the Polar Grip Revision 5 after Molding & Casting, ambient drying, polishing, and gluing.

3.2.2.2 Waterproof Breathable Fabrics

For Polar Grip Revision 5, commercial waterproof breathable fabrics were tested to identify the fabric that could replace the semipermeable layer (40 denier nylon treated with JHU/APL's hydrophobic coating) of Revision 4. The intent was to eliminate the immature laboratory process in order to ease the tech transfer effort. The eVent® reported in Progress Report #2 was identified as the best replacement. It has ~25% better breathability than the 40 denier nylon according to data collected at JHU/APL and its waterproofness is rated for a 100 ft water column according to vendor information (http://www.eventfabrics.com/products/#waterproof). JHU/APL has confirmed the rating up to 33 ft; the test apparatus needs modifications to accommodate testing to 100 ft.

The breathability of the layer allows sweat vapor from the skin and sweat-wicking liner to pass through the aerogel insulation liner and out to the inner surface of the cold rubber glove for condensation. The waterproofness results in the condensed water being collected at the hydrogel wrist band instead of allowing it to reach the aerogel. Additionally, we added the same eVent® fabric on the back of the aerogel tiles to cover up the extremely sticky PIB-coated backing layer that eases the insertion of the hand into the glove.

As seen in Fig. 2, the new prototype has demonstrated 3× better thermal performance compared to the control when exposed to sweating. Water collection efficiency will be quantified in the next phase after optimizing the glove fabrication and FFF, which also affects the efficiency.

3.2.2.3 IR-attenuating Fleece Gloves

The fleece in Polar Grip reduces IR radiation when the diver is outside water by thermally equilibrating the fiber tips with ambient, improving thermal protection and reducing thermal signature in air. The fleece also provides extra physical protection in water because the rubber glove of Polar Grip has been relatively thin. Because the fleece did not provide any extra thermal protection when it was soaked in water (Fig. 2), the fleece has been removed from the rubber glove for Revision 5 and made as a separate glove (Fig. 4a) unlike Revision 4, in which the fleece was glued to the outer surface of the rubber glove that faces swimming water. The fleece glove in Revision 5 can be optionally worn on top of the rubber glove when the diver is outside water. The thickness of the rubber glove will be optimized in future phases.

For the new prototype in this phase, three fleece gloves were fabricated by DRiS using fleece fabrics tested and reported in Progress Report #2 (Table 1) – thermal performance of the selected fabrics was on par with the polypropylene fleece used in Revision 4 and the surface temperature was reduced to within a few percentages of the ambient temperature.

Table 1. List of fleece fabrics used for the fleece glove of Polar Grip Revision 5 and their characteristics.

Fabric #	Name of fabric	Materials	Color	Approx. fiber length	Weight (GSM≡g/m^2)	Double-sided/ single-sided	Approx. thickness
1	Soft & minky fleece fabric	Polyester	White	3 mm	250 GSM	Single-sided	2 mm
2	Soft & comfy minky fabric	Polyester	White	3 mm	233 GSM	Single-sided	2 mm
3	Anti-Pill fleece fabric	Polyester	White	3 mm	380 GSM	Double-sided	3 mm

The thermal performance of the fleece glove was characterized in air using IR imagery (Fig. 6). As expected from Fig. 2, the overall performance of the Polar Grip Revision 5 was better than the control. Further glove engineering and optimization are necessary for additional improvements. Hot spots present in Revision 5, unlike Revision 4, were primarily attributed to the fourchettes added around fingers without aerogel insulation underneath. There was an additional hot spot in the wrist area because the aerogel insulation liner was not long enough to cover the wrist. The pictures in the last column of Fig. 6 also underscores the importance of the wind in convection cooling of the fiber tips in the fleece. The control also performed fairly well under the wind and further discussion should be made in the future regarding the practicality of the fleece glove and the optimum thickness of the rubber glove – the thickness of the rubber glove in Polar Grip was originally designed to be thin in order to compensate for the thick fleece.

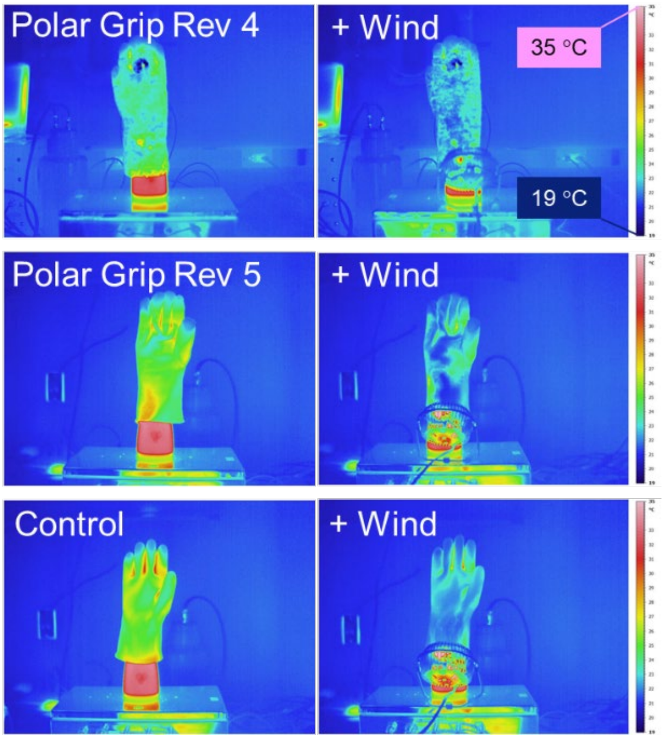


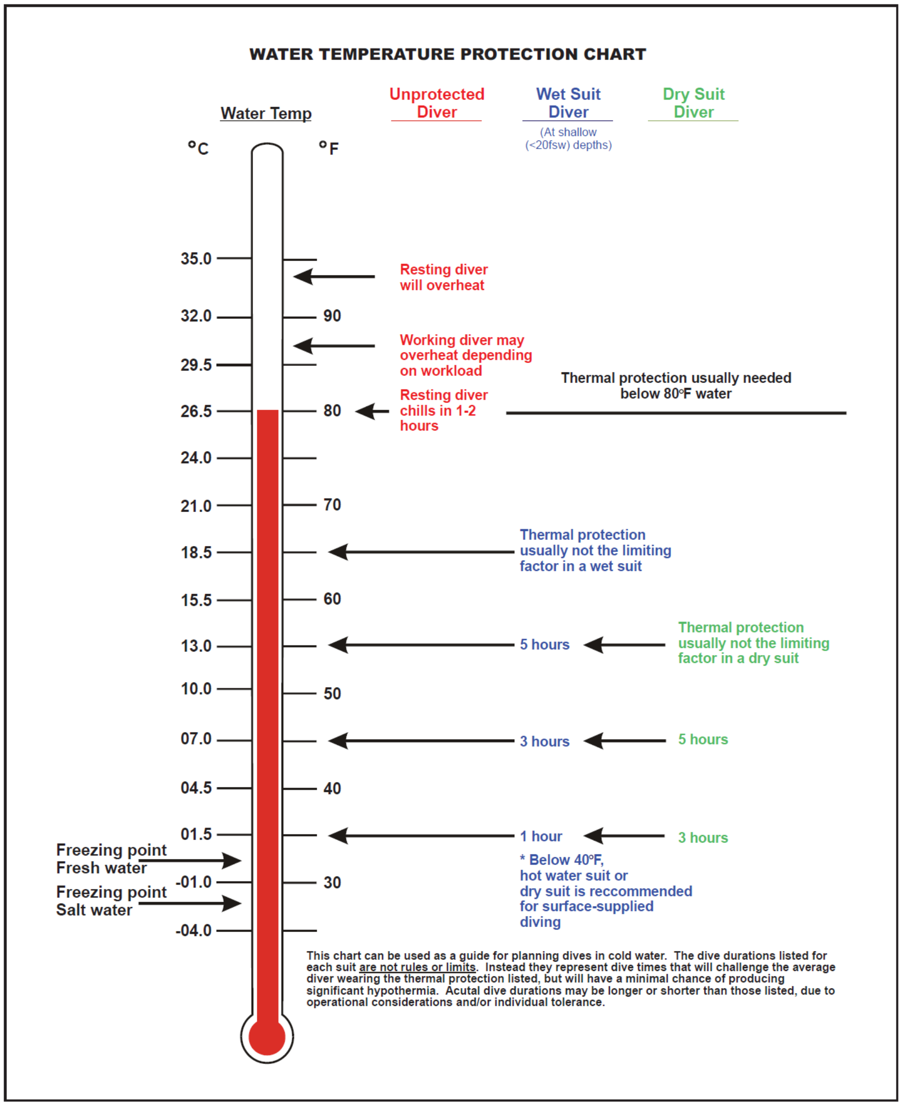
Figure 6. IR images of dry diving gloves including Polar Grip Revisions 4 and 5, and the control glove. While the addition of a 7 mph of wind can bring the apparent surface temperature very close to ambient and the fleece makes it more efficient, the thermal performance of the functional stack under the fleece is another important factor as concluded in the previous phase of study.

3.3 Operational Utility Assessment (Task #3)

The objective of this task was to determine the operational utility of Polar Grip by estimating mission duration in cold water through a potential underwater test at NEDU and by developing a new analytical model that can support the data from the test. After a discussion with NEDU, the team has determined that Polar Grip needs further improvement in FFF in order to conduct a more meaningful test at NEDU in the future and has decided to study the implication of sweating on the mission duration and the potential gain by Polar Grip from its strength against sweating.

3.3.1 Dive Duration in Cold Water

According to the chart in Fig. 7, the thermal protection becomes a limiting factor when the water temperature is below 13 °C and a mission can last only for an hour at water temperature of 1.5 °C – seawater temperature in Greenland Sea varies between 0.5 °C and 5 °C within 100ft water depth (https://en.wikipedia.org/wiki/Arctic_Ocean#/media/File:Temperature_and_salinity_profiles_in_the_Arctic_Ocean.svg).



This chart can be used as a guide for planning dives in cold water. The dive durations listed for each suit are not rules or limits. Instead they represent dive times that will challenge the average diver wearing the thermal protection listed, but will have a minimal chance of producing significant hypothermia. Acutal dive durations may be longer or shorter than those listed, due to operational considerations and/or individual tolerance.

Figure 7. Water temperature protection chart as a guide for planning dives in cold water (US Navy Diving Manual, Revision 7 (December 2016)).

The Nuckols' analytical thermos-physiological diver model further describes the level of thermal protection necessary for the diving duration required for the mission at a given water temperature (Fig. 8). Knowing the possible thermal performance in water by the control and Polar Grip, any mission longer than one hour is quite challenging in cold water below 5 °C requiring CLO higher than ~ 0.75.

The Nuckols' model does not account for the change in thermal protection as a function of water depth and an attempt has been made in this phase to upgrade the model in order to estimate mission duration as a function of water depth. The effort quickly turned out to provide little value for Polar Grip because the data collected in this study (Fig. 3) showed little change in the resistance with the pressure (i.e. water depth). In fact, this strongly underlines the benefit of having incompressible aerogel as an insulator in Polar Grip and its potential benefit in a full dry suit system. It was also less meaningful to apply the model using only data from the glove because the mission duration should be estimated based on the thermal protection by the entire suit system to be more realistic.

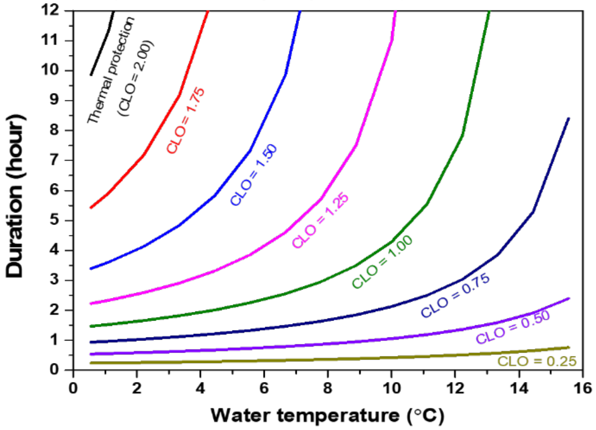

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Figure 8. Estimated mission durations for a resting diver in cold water based on Nuckols' analytical thermos-physiological diver model.

The reality in cold water is even harsher for divers who are required to conduct physical activities because sweat from the activities would further deteriorate the thermal protection – the model in Fig. 8 was based on a resting diver. While Polar Grip would be able to provide mission duration that is 3× longer than the current technology, assuming all others equal as concluded previously, it should be noted that the conclusion was based on 30 min sweating duration – all sweating data reported in past years have been based on 30 min sweating time. When the underwater activities continue beyond 30 min and presumably up to 3 hours, sweating would become more important. Data collected from the control glove, which does not have an ability to remove sweat, shows it would lose 68% of its thermal protection performance in 3 hours (Figure 9).

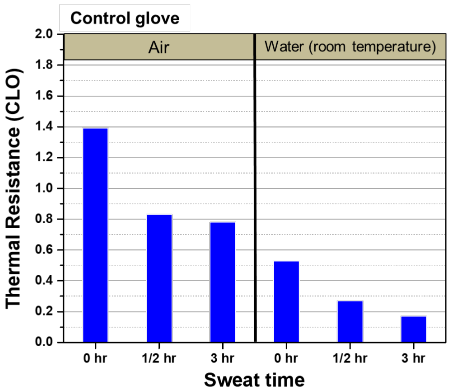

Figure 9. Change in thermal resistance of the control glove as a function of sweat time in air and water at room temperature.

The current Polar Grip materials, particularly the aerogel insulation, are not fully waterproof and further sweat testing will be conducted in the future after improving glove design and fabrication in order to prevent the degradation of materials due to direct contact with sweat.

The importance of sweating, particularly for missions conducted for an extended period, was further stressed by the team members with experience in military diving. The potential diving missions for an extended period are listed below.

- Navy SEALS, conducting the SEAL Delivery Vehicle missions that vary from 1-5 hours in length.
- Navy Underwater Construction Teams performing long duration surface supplied diving in dry suits.
- US Marine Corps Force Reconnaissance Divers conducting very shallow water dives – missions vary from 3-5 hours in shallow water and if water temperature dictates, they will be in a dry suit.

3.3.2 Thermal Performance and FFF

Polar Grip features flexible and incompressible aerogel tiles as its core technology to provide superior thermal protection over the current technology, which is not capable of supporting missions in cold water down to 100ft depths. The flexibility is an important element to optimize FFF of the glove and the necessary flexibility has been achieved by particular geometrical tile structures and patterns designed by JHU/APL. Another critical element that has not been much discussed is the thickness of the aerogel, which has a linear relationship with the thermal resistance of the glove. Although unintended, the thickness of titles made of Airloy® X116 for Revision 5 is 0.5-1 mm thinner than those made of Airloy® X103-M for Revision 4. The difference has been attributed to the sensitivity of Airloy® X116 against organic solvents and water as well as the immature polishing step and the potential extra shrinkage of Airloy® X116 during its drying process after casting. The ~1 mm difference in the thickness of the aerogel can alter its performance by 20-30%, which is not trivial. The more important unanswered question is whether its thickness is optimal for the required FFF, which is mostly qualitatively guided by Navy.

Future effort in improving FFF and seeking acceptance by military divers will require more advanced glove design in which the balance between rigid aerogel tile elements and FFF is achieved. One example effort includes adding stretchable slivers between banks of the tiles in order to maximize both FFF and the thickness of the tiles. Adding insulation to the fourchettes is also necessary to improve thermal protection of fingers.

4. Next Steps – Transition Phase I

4.1 Build Polar Grip Mockups for Frequent Glove Test (Task #1)

This task aims to establish the capability to fabricate Polar Grip mockups made of aerogel simulant, which enables a rapid turn-around time, permitting frequent glove testing and fabrication iterations, enabling a more coordinated effort in balancing FFF and thermal performance, and improving proficiency in glove fabrication. The current rate of Polar Grip fabrication is limited by a long lead time for acquiring aerogel material and its cost, and consequently, the effort by JHU/APL has been focused on the materials level performance. JHU/APL's expertise is in materials, not glove design and fabrication, per se, so data collected from the prototypes resulted in insufficient FFF. The process of engineering the mockups to optimize FFF is expected to improve the proficiency of the design optimization process. Materials level testing will also continue in parallel in order to differentiate the effect of materials from the effect of the glove design on the thermal performance of the glove. The thermal performance of the aerogel simulant made of generic polymers can be extrapolated to estimate the performance gain from the actual aerogel in the final prototypes.

4.2 Build a Sweating Hand Mannequin for Glove Test (Task #2)

In this task, a custom-made sweating hand mannequin will be fabricated in order to provide a capability to test gloves under simultaneous pressurized cold water and sweating conditions. The mannequin will be rated for hydrostatic pressure equivalent to 100 ft water depth and will have capabilities to measure temperature and heat flow at multiple places on the hand, and to sweat at a rate up to 1 liter/m^2/hr under the hydrostatic pressure, the rate necessary for a very physically active diver. This unique capability will generate data that have not been previously published in the field, providing comprehensive knowledge on glove performance under the conditions of interest, and enabling effective design feedback and optimization.

4.3 Optimize FFF, Thermal Performance & Sweat Management (Task #3)

A systematic approach will be taken to simultaneously optimize Polar Grip's FFF, thermal performance, and sweat management. The trade space between FFF and thermal performance will first be quantitatively characterized in order to define boundaries of the pathway to the future, which will be optimized through an engineering effort. Both materials selection for improving FFF and a routine to characterize FFF will be collaboratively established by Aqua Lung and JHU/APL. Thermal performance and sweat management will be characterized by JHU/APL.

4.4 Prototype Industry-standard Polar Grip (Task #4)

JHU/APL will work together with Aqua Lung to design the first generation of Polar Grip prototype that satisfies manufacturing, performance and commercialization requirements. Aqua Lung will fabricate the final prototype and JHU/APL will characterize its FFF and thermal performance. The final prototype is expected to meet NEDU standards for FFF; feedback from NEDU will be solicited throughout development to ensure development of an effective solution for divers and in preparation for a potential underwater test at NEDU in early Transition Phase 2, the last phase of Polar Grip.

5. Team Contribution

Task #1: Manufacturability	Dr. Michael Jin (task lead for Task #1)
	Dr. Bruce Trethewey and Douglas Trigg (contribution to company visits)
Task 2: Manufacturing Optimization	Drs. Jason Benkoski and Michael Jin (task lead for new aerogel layer development)
	Paul Biermann (fabrication of silicone mold)
	Steven Griffiths (Machine Slitting of aerogel tiles)
	Tessa VanVolkenburg and Douglas Trigg (testing waterproof breathable fabrics and fabrication of aerogel tiles)
	Dr. Xiomara Calderon-Colon (testing fleece fabrics)
	Jonathan Pierce, David Deglau, and William Luedeman (thermal resistance/resistivity measurement)
Task 3: Operational Utility Assessment	Dr. Michael Jin (task lead for Task #3)
	Dru Daubon and Stephen Phillips (consulting on military diving)

6. Financial Report

Grand Total	$136, 653 (fully funded and spent)