Thermal Characteristics of Diving Garments When Using Argon as a Suit Inflation Gas

Nuckols ML, Giblo J[*], Wood-Putnam JL[#]
Duke University, Durham, North Carolina, 27708
[*]Navy Clothing and Textile Research Facility, Natick, Massachusetts, 01760
[#]Naval Surface Warfare Center, Panama City Division, Panama City, Florida, 32407.

***Abstract*-The thermal insulation characteristics of two drysuit ensembles, consisting of the same tri-laminate outergarment with differing thermal undergarments, were measured on a 21-zone thermal manikin at the Navy Clothing and Textile Research Facility (NCRTF) during immersion testing when using air and argon alternatively as the suit inflation gas. Total thermal insulation values were determined for both garments utilizing ASTM test standard F 1291 – standard test method for measuring the thermal insulation of clothing using a heated manikin. Improvements in localized thermal insulation values were seen throughout both drysuit ensembles when using argon as an inflation gas when compared with those while using air. Improvements with argon inflation in an experimental aerogel garment ranged from a low of 11% in the legs, 27% in the arms, and 22% in the torso. Overall, the total suit insulation increased with the aerogel garment by approximately 16%. Improvements with argon inflation in a commercial drysuit ranged from a low of 5% in the torso, 12% in the arms, to a high of 32% in the legs. Overall, the total suit insulation increased with the commercial garment by approximately 20%. This investigation demonstrated that significant improvements in drysuit thermal protection can be achieved when using argon instead of air as a drysuit inflation gas. It should be noted however that these improvements were achieved by carefully and repeatedly purging (a minimum of 6 purge cycles) with pure argon prior to water entry. It is hypothesized that reduced thermal improvements have been seen in practice due to inadequate suit purging prior to dives.**

I. Introduction

Conventional materials used in the fabrication of diving garments rely on the entrapped gas (typically air) in the interstitial spaces of the garment material for thermal insulation. The inflation gas used during diving operations with variable volume drysuits plays a large factor in the thermal resistance of these garments [1]. For instance, the thermal resistance of a drysuit, R_T, is proportional to the suit thickness t and inversely related to the thermal conductivities K of the material fibers and the entrapped gas; ie

$$R_T \approx \frac{t}{K_{Gas} + K_{Fibers}} \qquad (1)$$

Thus, we can increase the thermal resistance of a diving garment by either increasing the garment thickness t, or select a suit inflation gas having a low thermal conductivity.

So, what constitutes a good suit inflation gas to minimize heat loss when diving with drysuits? Air is obviously a good choice since there exists minimal logistical issues and the cost is low. However, the advantage of using a gas having a lower thermal conductivity than air may outweigh any added logistics and expense provided that the improvement in suit insulation is worth the cost. The thermal conductivity of a gas is directly related to the molecular specific heat of the gas and inversely proportional to the product of the molecular size and the square root of the molecular mass; ie

$$K_{Gas} \approx \frac{C}{\sigma\sqrt{m}} \qquad (2)$$

where C is the specific heat per molecule, σ is the cross-sectional size of the molecule, and m is the mass of the molecule. This suggests that low thermal conductivity results with gases having minimum specific heats, and maximum molecular size and mass. Smaller molecules provide smaller targets to each other, creating fewer collisions; this enhances the direct transfer of heat from the diver's skin and through the suit. Also, molecules with low mass travel at greater velocities; this higher kinetic energy increases the transfer of heat during collisions.

The gas specific heat measures the quantity of heat that can be carried by a molecule. The quantity of heat carried by the molecule is related to its atomic structure and the degrees of motion possible for the gas molecule. For instance, monatomic molecules (gas molecules made up of a single atom) can move only in simple translation in the x, y, and z directions. All monatomic gases, including helium and all of the noble gases shown in Fig. 1, have identical molecular specific heats of 20.786 J/mol-^{o}K, the lowest specific heats per mol of all potential inflation gases; see Table 1.

U.S. Government work not protected by U.S. copyright

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **SEP 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **Thermal Characteristics of Diving Garments When Using Argon as a Suit Inflation Gas**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Navy Clothing and Textile Research Facility, , ,Natick,MA,01760**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002176. Presented at the MTS/IEEE Oceans 2008 Conference and Exhibition held in Quebec City, Canada on 15-18 September 2008.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

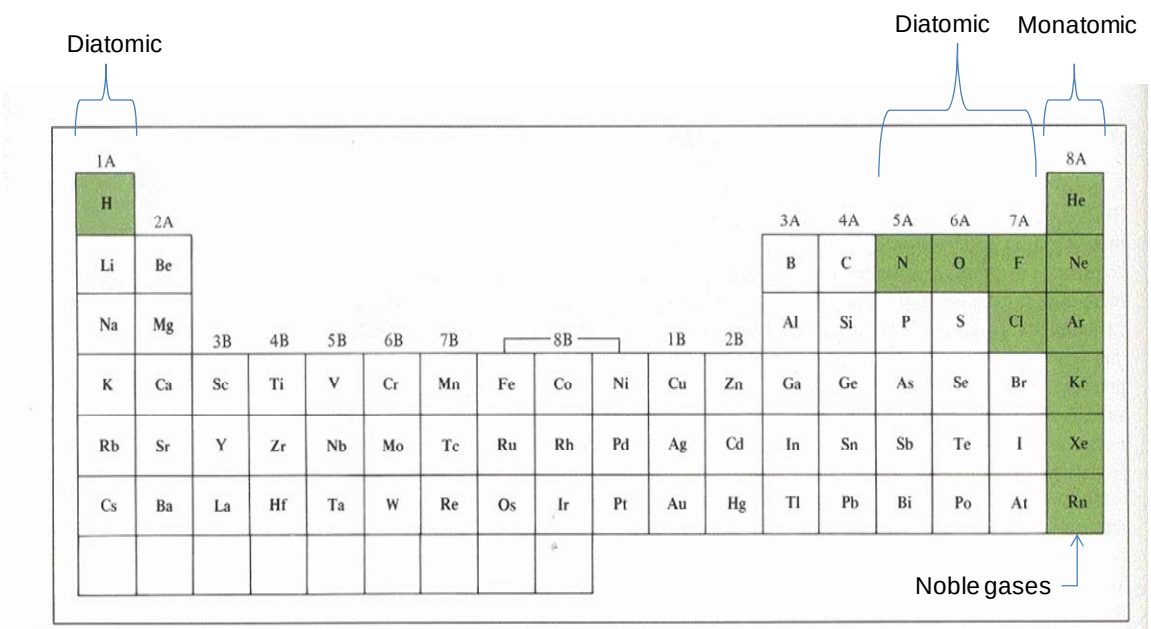
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

On the other hand, gases that exist as diatomic molecules, such as oxygen, nitrogen, and hydrogen can carry heat energy via translational (x, y, z) motion, as do monatomic gases, and also through rotational motion about the x, y and z axes. Due to the greater degrees of freedom, specific heats of diatomic gases are seen in Table 1 to be approximately 40% higher per molecule than the monatomic gases. Likewise, polyatomic gases, such as carbon dioxide (CO_2), sulfur hexafluoride (SF_6), and carbon tetraflouride (CF_4), can carry heat energy via translational motion, rotational motion, as well as vibrational motion between atoms in the molecule. Table 1 shows that this increased motion results in gas specific heats that are up to 4.5 times higher per molecule than monatomic gases.

Hydrogen would obviously be a poor choice as a suit inflation gas due to its diatomic structure, resulting in an elevated molecular specific heat, as well as its small molecular size and low mass (lowest of all the elements). In addition to its undesirable flammability issues, the combination in thermal and physical properties of hydrogen result in a gas having a thermal conductivity that is nearly 7 times greater than air; ie, $K/K_{air} \sim 7$.

TABLE I
THERMAL AND PHYSICAL PROPERTIES OF POTENTIAL SUIT INFLATION GASES

Gas	C, J/mol-°K	C, J/gm-°K	m, g/mol	σ, pm	K, mW/m-°K	K/K_{air}*
H_2	28.836	14.31	2.016	25	180.5	6.97
He	20.786	5.19	4.003	31	151.3	5.84
Air	28.97	1.00	28.97	--	25.9	1.00
N_2	29.124	1.04	28	65	25.83	1.00
O_2	29.378	0.92	32	60	26.58	1.03
Ne	20.786	1.03	20.18	38	49.10	1.90
Ar	20.786	0.52	39.95	71	17.72	0.68
Kr	20.786	0.25	83.80	88	9.43	0.36
Xe	20.786	0.16	131.29	108	5.65	0.22
Rn	20.786	0.094	222	120	3.61	0.14
CO_2	36.60	0.83	44	--	16.0	0.62
CF_4	58.0	0.66	88.01	--	15.03	0.58
SF_6	97.0	0.66	146.1	--	12.06	0.47



Water vapor (H_2O), CO_2, CF_4 and SF_6 are also gases with complex, polyatomic molecular structures

Fig. 1 Periodic table of elements. Elements existing as gases at 25°C are shown in green.

So why is helium not a good candidate for a drysuit inflation gas? A positive factor for helium is its monatomic structure, resulting in a low molecular specific heat. However, the contributions of small molecular size and low mass counteract this advantage, resulting in a thermal conductivity that is nearly 6 times greater than that of air (K/K_{air} = 5.84). Table 2 compares the contributing thermal factors of other inflation gas candidates relative to air. Carbon dioxide has a thermal conductivity which is approximately 62% in comparison with air in spite of the fact that it is a polyatomic gas. However, the production of a weak carbonic acid in the presence of water (sweat) on the diver's skin has been observed to cause skin rash, making it unattractive as a suit inflation gas. Other polyatomic gases, such as sulfur hexafluoride (commonly used as an inert filling for windows) and carbon tetraflouride (used as a low temperature refrigerant), likewise offer a thermal advantage, but the improvement in suit insulation is generally not considered worth the expense (SF_6 and CF_4 are both known greenhouse gases and CF_4 has been shown to cause heart damage from long-term exposures).

By far, the lowest thermal conductivities are seen with the large, monatomic gases, including krypton, xenon, and radon. Theoretically, radon could be used to reduce the heat transfer through a diver's garment considerably (K/K_{air} = 0.14) if it were not a naturally occurring radioactive gas, and the second most frequent cause of lung cancer after cigarette smoking. Xenon and krypton also offer superior thermal potentials, but their costs (approximately $1000 per standard cubic foot) make them not practical for diving operations.

TABLE 2
CONTRIBUTING FACTORS IN SUIT INFLATION GAS SELECTION

Gas	Structure		Mass		Size		K/Kair	
Hydrogen	Diatomic	✗	Lowest	✗	Small	✗	6.97	Worst case
Helium	Monatomic	✓	2nd low	✗	Small	✗	5.84	Poor
CO2	Polyatomic	✗	High	✓	Large	✓	0.62	Skin rash
SF6	Polyatomic	✗	High	✓	Large	✓	0.47	Cost
CF4	Polyatomic	✗	High	✓	Large	✓	0.58	Cost
Radon	Monatomic	✓	High	✓	Large	✓	0.14	RA
Xenon	Monatomic	✓	High	✓	Large	✓	0.22	~$1000
Krypton	Monatomic	✓	High	✓	Large	✓	0.36	per scf
Argon	Monatomic	✓	High	✓	Large	✓	0.68	Good Compromise

Argon gas has frequently been used by cave divers and technical divers as a drysuit inflation gas to augment thermal protection when diving in cold water. While argon has a thermal conductivity that is approximately 32% lower than that of air, not all are in agreement as to the thermal benefits that can be achieved with argon suit inflation [2]. The objective of this study, sponsored by the Office of Naval Research, was to quantify, using thermal manikin testing, the potential thermal benefits that are obtainable when using argon instead of air as a drysuit inflation gas.

II. MATERIALS AND METHODS

The thermal insulation characteristics of two drysuit ensembles, consisting of the same tri-laminate outergarment with differing undergarments, were measured on a 21-zone thermal manikin at the Navy Clothing and Textile Research Facility (NCRTF), Fig. 2, when using air and argon alternatively as the suit inflation gas. The first thermal undergarment consisted of an experimental liner constructed from a super-insulating aerogel fabric. The second liner was a commercially-available, off-the-shelf garment constructed as a one-piece coverall. Total thermal insulation values were determined for both garments utilizing ASTM test standard F 1291 – standard test method for measuring the thermal insulation of clothing using a heated manikin [3]. Suit insulation values were measured by recording the electrical power levels required to be delivered to each manikin zone to maintain a fixed manikin skin temperature of 30°C (86°F) while submerged in a constant temperature water bath. Prior to

manikin submergence, the drysuits were repeatedly inflated and then purged with either air or industrial grade argon for a minimum of 6 cycles to insure the purity of the inflation gas inside the drysuit; see Fig. 3 through Fig. 5.

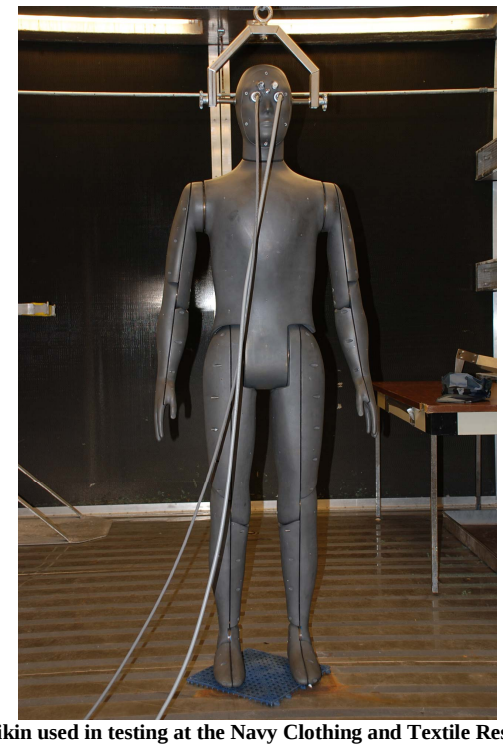


Fig. 2 21-zone thermal manikin used in testing at the Navy Clothing and Textile Research Facility in Natick, MA.

Fig. 3 Manikin outfitted with a tri-laminate drysuit and 3-finger gloves over the sample aerogel garment.

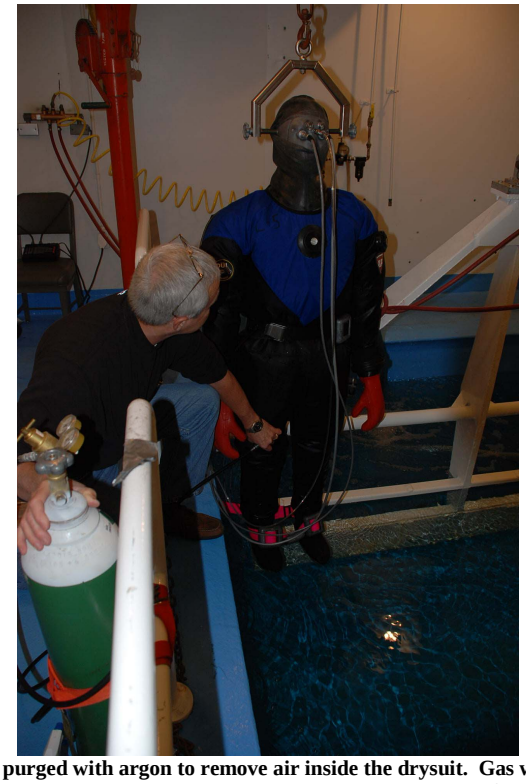


Fig. 4 Garment being repeatedly inflated and purged with argon to remove air inside the drysuit. Gas was added through a suit inflation valve located on the right thigh and then vented to the atmosphere through the suit exhaust value located on the left upper arm. Six complete inflation/exhaust cycles were completed prior to final inflation prior to immersion.

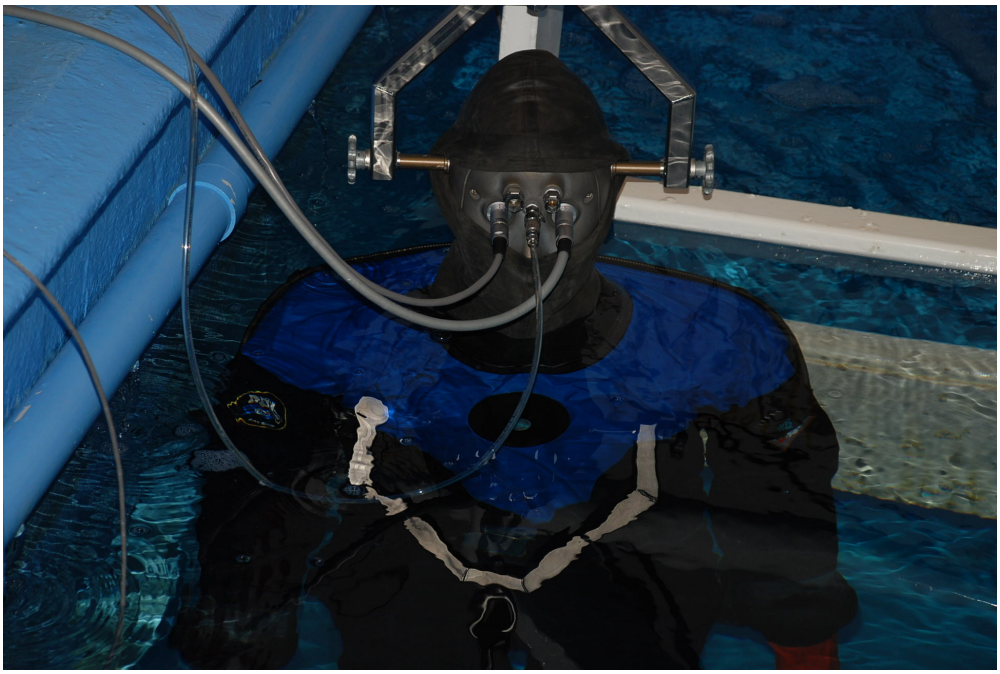


Fig. 5 Manikin submerged in a constant temperature test pool to neck level.

III. Results

Improvements in localized thermal insulation values, measured in units of CLO[1], were seen throughout both drysuit ensembles when using argon as an inflation gas when compared with those while using air. Fig. 6 shows improvements with argon inflation in the aerogel garment ranged from a low of 11% in the legs, 27% in the arms, and 22% in the torso. Overall, the total suit insulation, minus head, hands, and feet (-HHF), increased with the aerogel garment by approximately 16%.

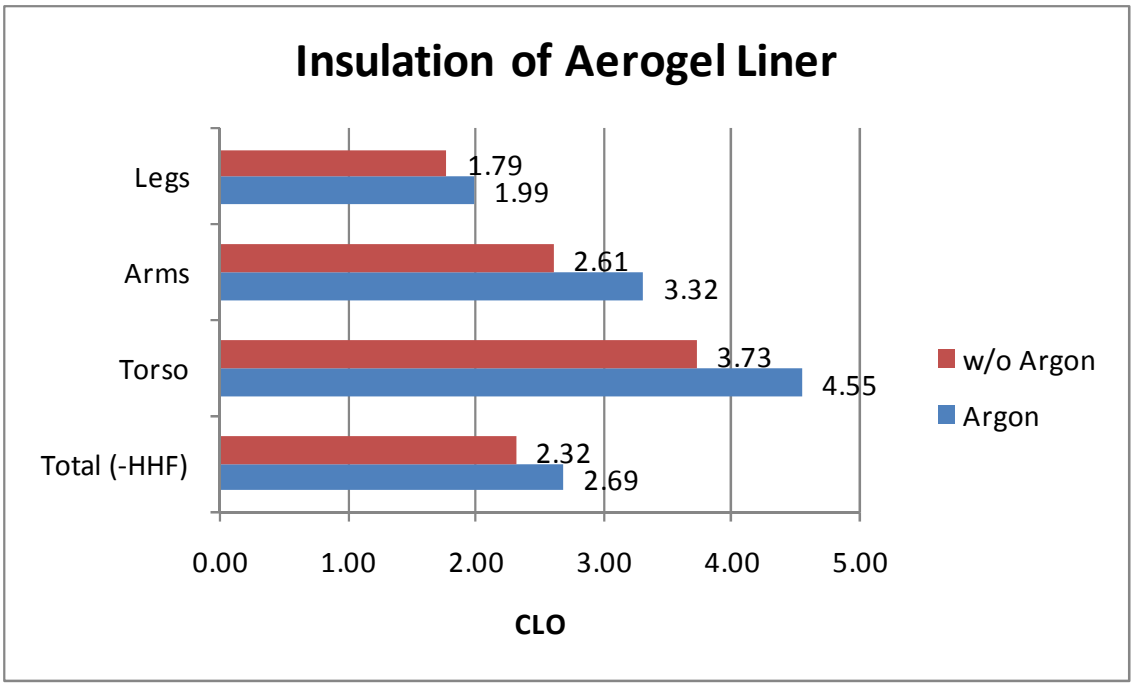


Fig. 6 Effect of argon as a suit inflation gas with the aerogel garment.

Fig. 7 shows improvements with argon inflation in the commercial drysuit ranged from a low of 5% in the torso, 12% in the arms, to a high of 32% in the legs. Overall, the total suit insulation, minus head, hands, and feet (-HHF), increased with the commercial garment by approximately 20%.

[1] CLO as a unit of thermal protection can be characterized as the insulation inherent in a business suit when worn in air [4]. It can be quantified as 6.452 divided by the suit conductance, where suit conductance is measured in watt/m^2-^{o}C; ie

$$CLO = \frac{6.452}{\left(Suit\,Conduc\tan ce, \frac{watts}{m^2 - {}^oC} \right)}$$

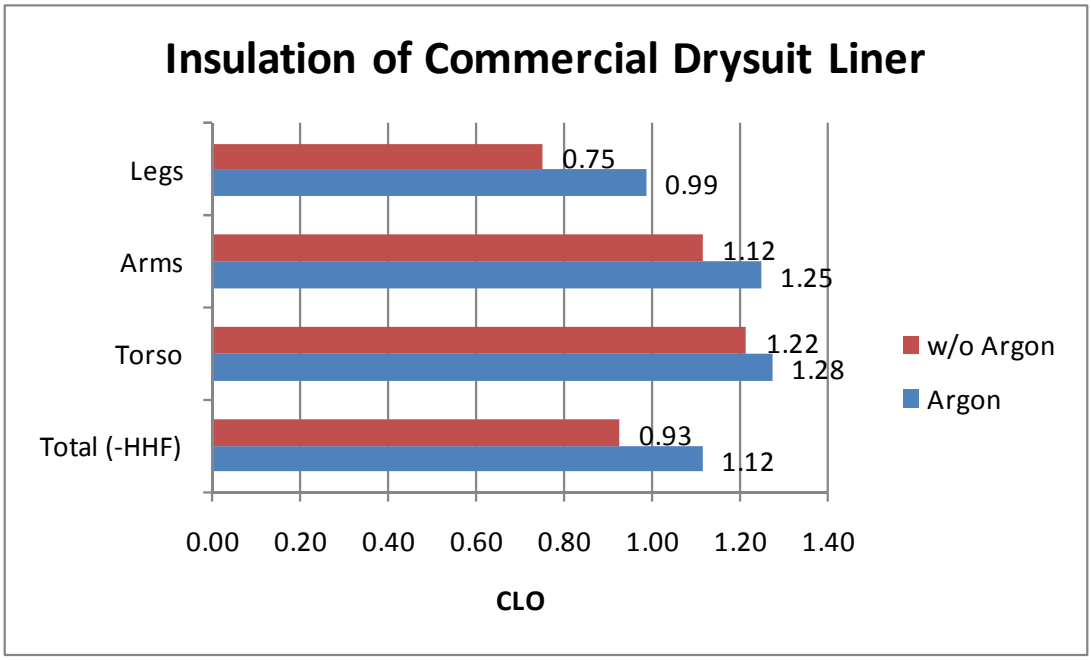


Fig. 7 Effect of argon as a suit inflation gas with the commercial drysuit garment.

IV. Conclusions

This investigation has demonstrated that significant improvements in drysuit thermal protection can be achieved when using argon instead of air as a drysuit inflation gas. It should be noted however that these improvements can only be achieved by carefully and repeatedly purging (a minimum of 6 purge cycles) with pure argon prior to water entry.

Acknowledgment

This research was made possible through funding from the Ocean Engineering and Marine Systems Science and Technology Program, Office of Naval Research, ONR Code 321CG.

References

[1] E. Maiken, "Why Argon," http://www.decompression.org/maiken/Why_Argon.htm

[2] J. Risberg, A. Hope, "Thermal Insulation Properties of Argon Used as a Dry Suit Inflation Gas," *Undersea Hyperbaric Medicine*, 28(3), pp. 137-143, 2001 Fall.

[3] ASTM Standard F1291, 2005, "Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin," ASTM International, West Conshohocken, PA, www.astm.org

[4] A. Gagge, J. Hardy and G. Rapp, "Proposed Standard System of Symbols for Thermal Physiology," *Journal of Applied Physiology*, vol 27, pp: 439-446, Sept 1969.