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**INSULATIVE PROPERTIES OF TWO
THERMO-METAL NEOPRENES**

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EXECUTIVE SUMMARY

Recently, Yamamoto Corporation introduced on the market a new type of diving suit fabric called thermo-metal neoprene. It consists of a closed-cell neoprene with the inner cloth lining coated with metal. The metal-coated lining is claimed to act as a reflective barrier that minimizes radiative heat loss from the body and hence, improves the thermal properties of the fabric by 25% over uncoated neoprene. The objective of the present study was to verify the claims of the manufacturer by comparing the insulation of two thermo-metal neoprenes (titanium and stainless steel coated) to the current Canadian Forces Arctic diving suit neoprene (CF-N) in a dry environment at 1 atmosphere and in a wet environment under various pressures to simulate dives up to 100 m.

It was found that the thermal insulation of the two thermo-metal neoprenes tested was significantly higher than that of the CF-N in both the dry and the wet environments. The best thermo-metal neoprene, the stainless steel coated neoprene, averaged an improvement of 53-60% over the CF-N depending upon the testing environment. The insulative properties of the thermo-metal neoprenes were affected, however, by the dives, decreasing by about 12% after two dives.

It was concluded that the stainless steel thermo-metal neoprene could be a potential alternative to the current CF Arctic diving suit neoprene but further testing is needed on the long term effects of dives and aging on the insulative properties of the material.

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ABSTRACT

The objective of the present study was to compare the thermal resistance of two thermo-metal neoprenes (titanium and stainless steel coated) to the current Canadian Forces Arctic diving suit neoprene (CF-N) in dry and wet environments. The tests in the dry environment were conducted using a Rapid-k thermal conductivity instrument, and in the wet environment using a custom-made apparatus. The dry tests were conducted at 1 atmosphere in the laboratory, and the wet tests were done in a hyperbaric water chamber maintained at 5°C and at depths of 0, 10, 25, 50, and 100 m. Pre and post-dive tests were performed on the same samples to investigate the effects of two dives on the thermal resistance of the neoprenes.

It was found that the thermal insulation of the two thermo-metal neoprenes tested was significantly higher than that of the CF-N in both the dry and the wet environments. The best thermo-metal neoprene, the stainless steel coated neoprene, averaged an improvement of 53% in the dry and 60% in the wet environment (ranging from 70% at 0 m to 34% at 100 m). The insulative properties of the thermo-metal neoprenes were affected, however, by the dives, decreasing by about 12% after two dives.

It was concluded that the stainless steel thermo-metal neoprene could be a potential alternative to the current CF Arctic diving suit neoprene but further testing is needed on the long term effects of dives and aging on the insulative properties of the material.

INTRODUCTION

The Experimental Diving Unit (EDU) at DCIEM is currently looking for alternatives to improve the present Canadian Forces (CF) Arctic diving suits. During the past two years, a new type of wet suit fabric called thermo-metal neoprene, which consists of a metal-lined closed-cell neoprene, was introduced on the market by Yamamoto Corporation. The inner lining of the neoprene is made of woven fabric coated with either titanium or stainless steel. The manufacturer claims that these materials are 25% more thermally efficient than competitive products due to the reflective thermal barrier that controls the absorption and reflection of radiant body heat.

The objective of the present study was to determine the validity of the manufacturer's claims and to compare the thermal resistance of two thermo-metal neoprenes (titanium and stainless steel coated) to the current CF Arctic diving suit neoprene in dry and wet environments.

MATERIALS AND METHODS

Neoprene samples. Three one-foot-square samples of closed-cell neoprene (28.7 x 28.7 cm) were tested: a sample of the current CF Arctic diving suit neoprene (CF-N; Rubatex G-231, 6.4 mm thick, Rubatex Corporation, Bedford, Virginia, U.S.A.; NATO Stock Number 4220-21-871-7222, Specification (CFTO) number C87001001SF001), and samples of the titanium (TT-M; 7.1 mm thick) and the stainless steel (SS-M; 7.7 mm thick) coated thermo-metal neoprenes (Yamamoto Corporation, Osaka, Japan).

Thermal resistance measurements. To compare the thermal insulative values of the three neoprene materials, we evaluated their thermal resistances in a dry environment (R_d) at 1 atmosphere and in a wet environment during dives to five different depths ranging from 0 to 100m (R_{w0} , R_{w10} , R_{w25} , R_{w50} , R_{w100}).

Determination of R_d . The thermal resistances of the neoprene materials were measured in the dry environment (dry test) using a Rapid-k instrument (Dynatech R/O Company, Mass). The Rapid-k is an apparatus designed to determine the thermal conductivity of materials in accordance

with ASTM C518 "Specifications for the Measurement of Thermal Conductivity by Means of the Heat Flow Meter". The heat flow meter of the Rapid-k was previously calibrated against 2 thermal resistance standards from the Thermal Performance Section of the National Research Council of Canada (MDGB Transfer Standards #357-172-A,B; see Ducharme and Frim, 1991).

The R_d values (in $^{\circ}\text{C}\cdot\text{m}^2\cdot\text{W}^{-1}$) for the different neoprene materials were calculated using the Fourier linear heat flow equation as follows:

$$R_d = \frac{T_u - T_l}{H_{\text{rapid-k}}}$$

where T_l is the average temperature (in $^{\circ}\text{C}$) of the lower face of the neoprene sample (in contact with the cold copper plate of the Rapid-k), T_u is the average temperature (in $^{\circ}\text{C}$) of the upper face of the neoprene sample (in contact with the hot copper plate of the Rapid-k), and $H_{\text{rapid-k}}$ is the average heat transfer from the upper to the lower face of the sample (in $\text{W}\cdot\text{m}^{-2}$). Two different levels of heat flux were used to measure R_d : a low flux ($\sim 80 \text{ W}\cdot\text{m}^{-2}$) and a higher flux ($\sim 250 \text{ W}\cdot\text{m}^{-2}$). The reported values of R_d are averages of resistances measured for the two heat fluxes for every neoprene material. Since the heat flux sensor of the Rapid-k is located in a central 10 cm x 10 cm area called the "effective area" (to ensure unidirectional and uniform heat flux from the upper to the lower plate), all temperature measurements were restricted to that area of the sample. T_l and T_u represent average readings from 3 thermocouples (AWG 40) located within the effective area. All data reported were collected at thermal steady state which was considered established when the R_d values changed less than 1% over a 20-min period, which took an average of 103.1 ± 11 min (mean \pm SE) to achieve. The temperature and heat flux data were collected several times a minute and averaged over a 1-min period using a data acquisition system (HP 3497A data acquisition control unit, Hewlett Packard). A constant pressure of 60 pounds was applied on the

samples during the testing to assure good contact with the copper plates of the Rapid-k. The pressure was not sufficient to create noticeable compression of the neoprenes.

Determination of R_w . The objective of these measurements was to investigate the effect of pressure and wetness on the thermal performance of the neoprene materials (wet tests). The tests were conducted in a hyperbaric chamber (Unmanned Test Facilities of EDU) partially filled with stirred water maintained at 5°C in which a custom made temperature controlled water bath was partially immersed and maintained at 35°C to allow a transfer of heat through the test material fixed to the bottom of the bath. Figure 1 describes the experimental apparatus for the wet testings. It consisted of a double-walled brass bath (40 x 40 x 40 cm) having a 5 cm thick insulation along its four vertical walls and a rigid brass uninsulated bottom. The water in the bath was well stirred and heated to 35°C with two immersion heaters controlled by a proportional temperature controller (YSI model 72, Yellow Springs, Ohio). The neoprene test sample was sandwiched between the bottom part of the bath (acting as a hot plate) and the "test bed" (acting as a cold plate). The test bed consisted of a 1 cm thick aluminium plate (40 x 40 cm) and a 0.6 cm Teflon® bed (30 x 30 cm) on which four recalibrated heat flux transducers (HFTs; model HA13-18-10-P(C), Thermonetics Corporation, San Diego, CA; see Ducharme et al, 1990 for calibration procedure) were fixed on the 10 x 10 cm central effective area of the Teflon® bed. Three calibrated thermocouples (AWG 40) were fixed on the effective area of the upper face of the neoprene sample and three on the lower face. The thermal resistances of the neoprene samples were measured using the same formula as for the dry tests. The heat flux used for the measurement of R_w varied with the depth of the dives due to changes in the thickness of the neoprene samples with pressure (~150 W·m⁻² at 0 m to ~500 W·m⁻² at 100 m). It took an average of 198.2 ± 30 min to achieve thermal steady state during the wet tests.

Experimental procedures. Only one sample of each neoprene material was used for all the dry and wet tests. Two dry and two wet tests were performed on the CF-N and on the best

thermo-metal neoprene (SS-M); only two dry tests were performed on the other thermo-metal neoprene (TT-M). The first test performed on the neoprene samples was Dry Test 1, followed by the two series of dives (Wet Test 1 and 2), and six months after the dives, by a second dry test on the same neoprene samples (Dry Test 2). The objective of testing the same neoprene samples was to investigate the changes in the thermal properties of the neoprene samples following dives.

The wet tests consisted of a series of 2 dives performed over a 3-week period. Each dive lasted about 4 days, starting with a dry test at 1 atmosphere performed with the wet apparatus (the cold water level was just below the neoprene sample but touching the aluminium plate). The objective of this dry test was to verify that wet test apparatus could reproduce the results of the dry test performed with the Rapid-k. This was followed by a 12 h period to wet the samples (the samples were sandwiched between the test bed and the bottom of the brass bath) and by a step dive at 0, 10, 25, 50, and 100m. R_w was measured at thermal steady state for every step of the wet tests (R_{w0dry} , R_{w0} , R_{w10} , R_{w25} , R_{w50} , R_{w100}) when R_w values changed less than 1% over a 20-min period. The two dive sequences Wet Test 1 and 2 were separated by one week.

Statistical analysis. The data were analysed by a two factor (type of neoprene, effect of dives) analysis of variance for repeated measures to determine the difference between values of thermal resistance during Dry Tests 1 and 2, using SuperAnova Statistical Programme for General Linear Modelling (Abacus Concepts Inc., Berkeley, CA, 1989). When the F-ratio proved significant, the Mean Contrast Test was used to locate significance between the means (using the Greenhouse-Geisser adjusted p-value). Where applicable, data are presented as mean \pm SE. The level of statistical significance was set at $p < 0.05$, unless otherwise stated.

RESULTS

Thermal resistances in dry environment. The R_d values measured at two different heat fluxes with the Rapid-k instrument differed only by an average of $2.8 \pm 0.8\%$ for each neoprene material tested. Figure 2 shows the average thermal resistance values at thermal steady state for

each sample tested during the Dry Test 1 (before the dives) using the Rapid-k instrument. It is observed that the two thermo-metal neoprenes have R_d values significantly higher than that of the CF-N, the TT-M being 25% better and the SS-M 53% better than the CF-N.

Thermal resistance in wet environment. Only the thermo-metal neoprene having the best resistance during the dry test (SS-M) was chosen for the wet tests. The thermal resistance values measured with the wet test apparatus in a dry environment (R_{w0dry}) were very close ($0.1172 \text{ } ^\circ\text{C}\cdot\text{m}^2\cdot\text{W}^{-1}$ for CF-N; $0.1875 \text{ } ^\circ\text{C}\cdot\text{m}^2\cdot\text{W}^{-1}$ for SS-M) to the R_d values measured with the Rapid-k ($0.1174 \text{ } ^\circ\text{C}\cdot\text{m}^2\cdot\text{W}^{-1}$ for CF-N; $0.1801 \text{ } ^\circ\text{C}\cdot\text{m}^2\cdot\text{W}^{-1}$ for SS-M). In fact, the $2.1 \pm 1.1\%$ percent deviation between the R_d and R_{w0dry} values was well within the deviation observed between the two R_d values measured for different heat fluxes ($2.8 \pm 0.8\%$). These results confirm the validity of the wet test apparatus for the measurement of the thermal resistances of the neoprenes. Figure 3 shows the thermal resistance values at thermal steady state for the SS-M and CF-N during Wet Test 1 for five different immersion depths ranging from 0 to 100 m. The R_w values decreased exponentially for both neoprenes (from $0.1102 (R_{w0})$ to $0.0111 \text{ } ^\circ\text{C}\cdot\text{m}^2\cdot\text{W}^{-1} (R_{w100})$ for the CF - N and from $0.1877 (R_{w0})$ to $0.0149 \text{ } ^\circ\text{C}\cdot\text{m}^2\cdot\text{W}^{-1} (R_{w100})$ for the SS-M) with an increase of immersion depth. On average, for all depths tested, the R_w values were 60% higher for the SS-M neoprene than for the CF-N. The difference decreased with depth from 70% at 0 m to 34% at 100 m. The R_w values from the Wet Test 2 were lower than for the Wet Test 1 for the SS-M neoprene (by about 10%) but not for the CF-N neoprene. The R_w values were on average 42% higher for the SS-M neoprene than for the CF-N. Again, the difference decreased with depth from 48% at 0 m to 23% at 100 m.

Effect of dives on thermal resistance values. Figure 4 shows the effect of two dives and a six-month "rest" period on the thermal resistance values of the three neoprene materials tested at thermal steady state in a dry environment at 1 atmosphere (only the TT-M was not submitted to a second dive series). The R_d values are significantly different among the three neoprene materials for the PRE and POST conditions, with the SS-M neoprene having R_d values 53 and 31% higher

than the CF-N for the PRE and POST conditions, respectively. Only the SS-M neoprene shows a significant decrement (12%) in R_d from PRE to POST condition (from 0.1801 to 0.1577 $^{\circ}\text{C}\cdot\text{m}^2\cdot\text{W}^{-1}$).

DISCUSSION

The results of the present study clearly show that the thermal resistances of the two thermo-metal neoprenes tested are significantly higher than that of the CF Arctic diving suit neoprene, and that the better thermo-metal neoprene is the stainless steel (SS-M) coated neoprene (53% better in a dry environment). However, samples also differed in thickness, which could account for some of the difference in insulation. When the thermal performance of the neoprene materials is expressed as thermal conductivity to account for thickness (CF-N: $0.0541 \text{ W}\cdot^{\circ}\text{C}^{-1}\cdot\text{m}^{-1}$; TT-M: $0.0486 \text{ W}\cdot^{\circ}\text{C}^{-1}\cdot\text{m}^{-1}$; SS-M: $0.0423 \text{ W}\cdot^{\circ}\text{C}^{-1}\cdot\text{m}^{-1}$), the SS-M neoprene still shows a 22% improvement (i.e. a decrease in conductivity) compared to the CF-N. While studies reported by Fourt and Harris (1968) showed that exposed metallic surfaces can act as a thermal barrier and significantly increase the thermal resistance of clothing, the present study cannot separate the effect of neoprene thickness and /or structure from fabric metal coating on insulation improvement. It was observed under magnification that the size of the gas bubbles in the CF-N is much larger than in the Yamamoto neoprene due to different methods of expansion of the neoprene materials. The Rubatex G-231 is made by external gassing (injection of nitrogen gas) and Yamamoto neoprene is made by chemical reaction. The difference in the structure of the neoprenes could be responsible for much of the difference observed in the resistance values. Further studies are required to compare the thermal resistances of the SS-M neoprene with and without the reflective layer.

The tests performed in the wet environment show that the insulative properties of the SS-M neoprene were more affected by the depth of the dives than the CF-N. This is in agreement with recent observations comparing the thicknesses of the two neoprenes during real dives which showed that Yamamoto neoprene compresses more than Rubatex G-231 neoprene at the same depth (Frew, 1993; unpublished observations). Despite this compression, the thermal resistance of

the SS-M neoprene remains higher than that of the CF-N for the whole range of depths tested. Again, the present study can not attribute the difference in thermal resistances to either the reflective barrier or the neoprene material. It is well known, however, that water absorbs infrared radiation (Adkins, 1987), and if water was present inside the woven reflective layer of the SS-M, then it should have nullified any advantages provided by the metal reflective barrier. Because the thermal resistance of the SS-M was greater than that of the CF-N even in wet conditions, it is possible that the difference in thermal resistance was due to the difference in the neoprene materials. Another possibility is that the neoprenes were not completely soaked with water during the wet tests and, therefore, the reflective barrier was still effective. Further tests need to be done to answer these questions.

The dives had a significant impact on the SS-M neoprene by decreasing its thermal resistance by 12% following two series of dives. No significant decrease in thermal resistance was observed for the CF-N, and no evidence of lasting compression of the neoprenes or physical alteration of the metal reflective layer was observed for the SS-M neoprene six months after the dives. Although the present study can not conclude what property of the SS-M neoprene has been affected by the dives, it is common knowledge in the diving community that the Yamamoto neoprene is more affected by dives than the Rubatex G-231 neoprene (Eaton, 1993; personal communication). Further studies both in the field and in the laboratory are essential to investigate the long term effects of dives on the thermal resistance of the thermo-metal neoprenes.

In conclusion, this study on the thermal properties of thermo-metal neoprenes shows that these neoprene materials have higher thermal resistance values than the current CF Arctic diving suit neoprene in dry and wet environments and under pressures simulating dives up to 100 m. The insulative properties of the thermo-metal neoprenes, however, are prone to deterioration following dives and further studies are necessary to fully evaluate their potential for the Canadian Forces.

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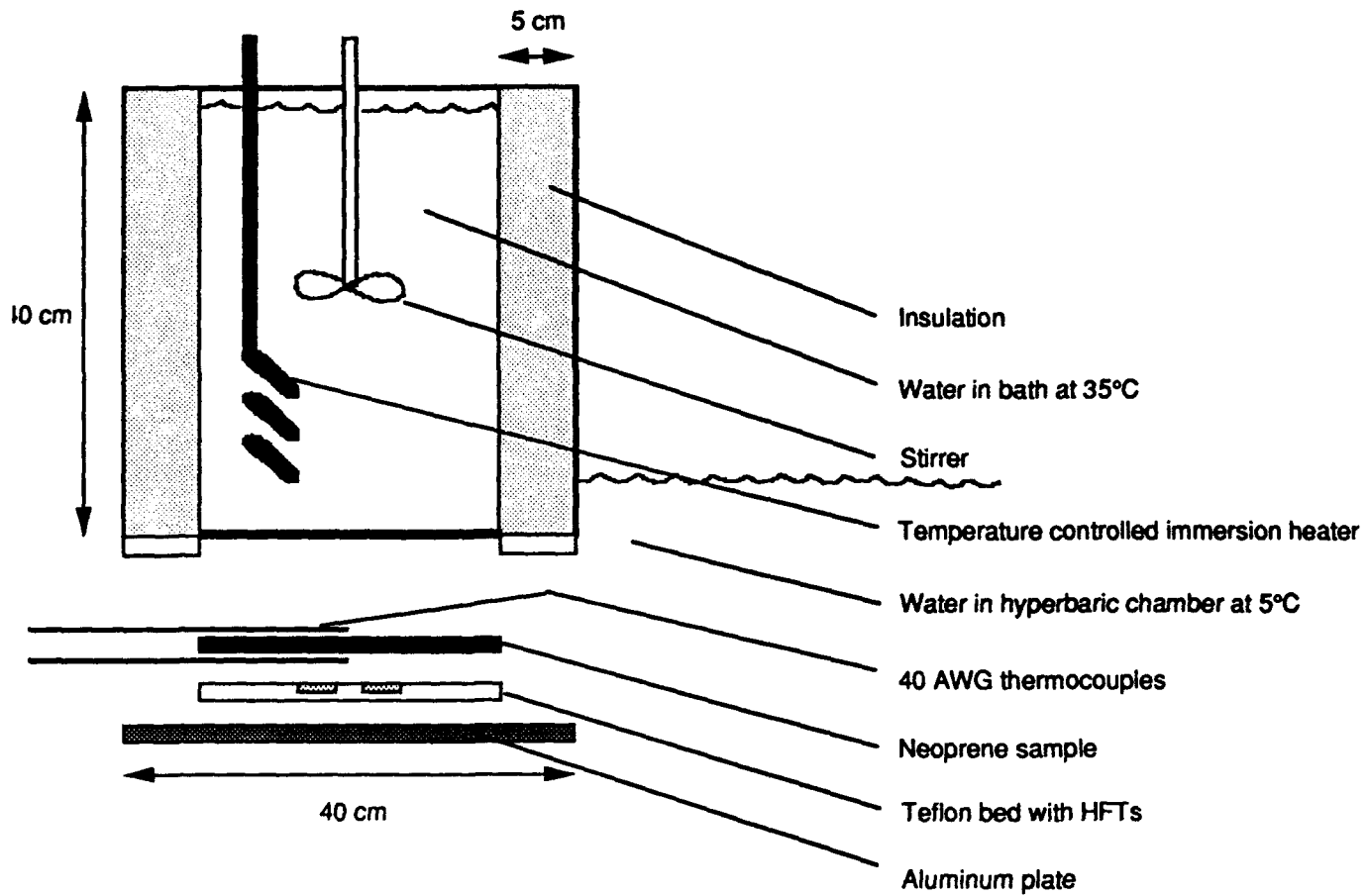


Fig.1 Experimental set-up for testing in the wet environment. The tests were performed in the EDU hyperbaric chamber at DCIEM.

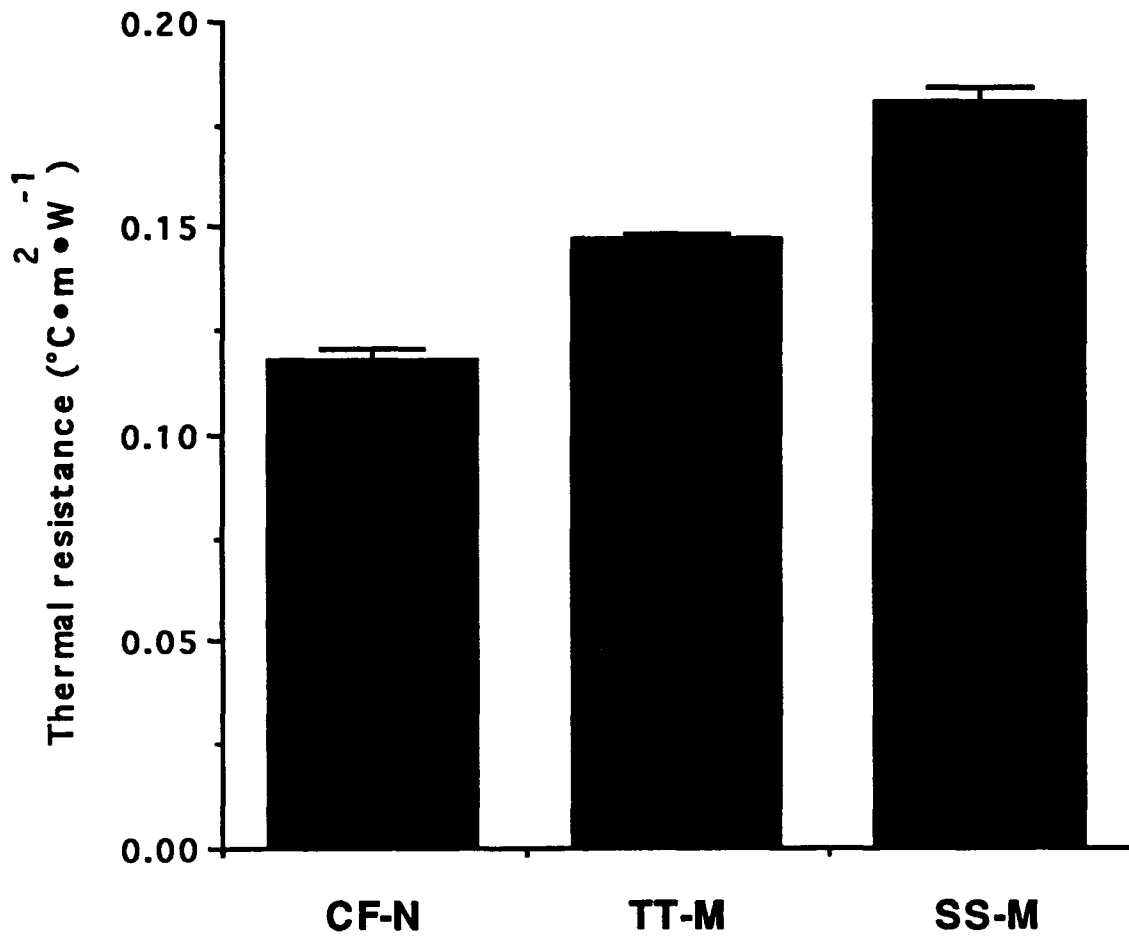


Fig.2. Thermal resistance of two thermo-metal neoprenes [titanium coated (TT-M); stainless steel coated (SS-M)] and of the current CF diving suit neoprene (CF-N) at thermal steady state in a dry environment (Dry Test 1). Each value is an average of two measurements (\pm SE) at different heat fluxes on the Rapid-k.

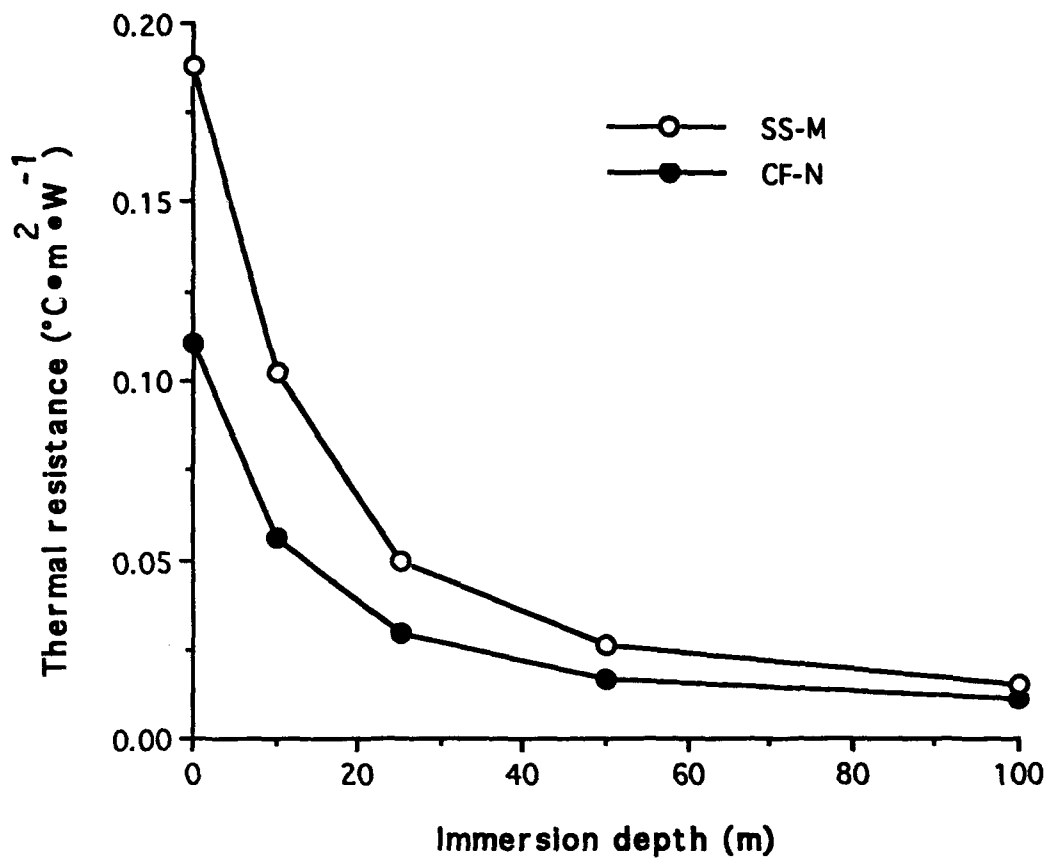


Fig.3. Thermal resistance of a thermo-metal neoprene (stainless steel coated; SS-M) and of the current CF Arctic diving suit neoprene (CF-N) at thermal steady state in a wet environment and under five different pressures during Wet Test 1.

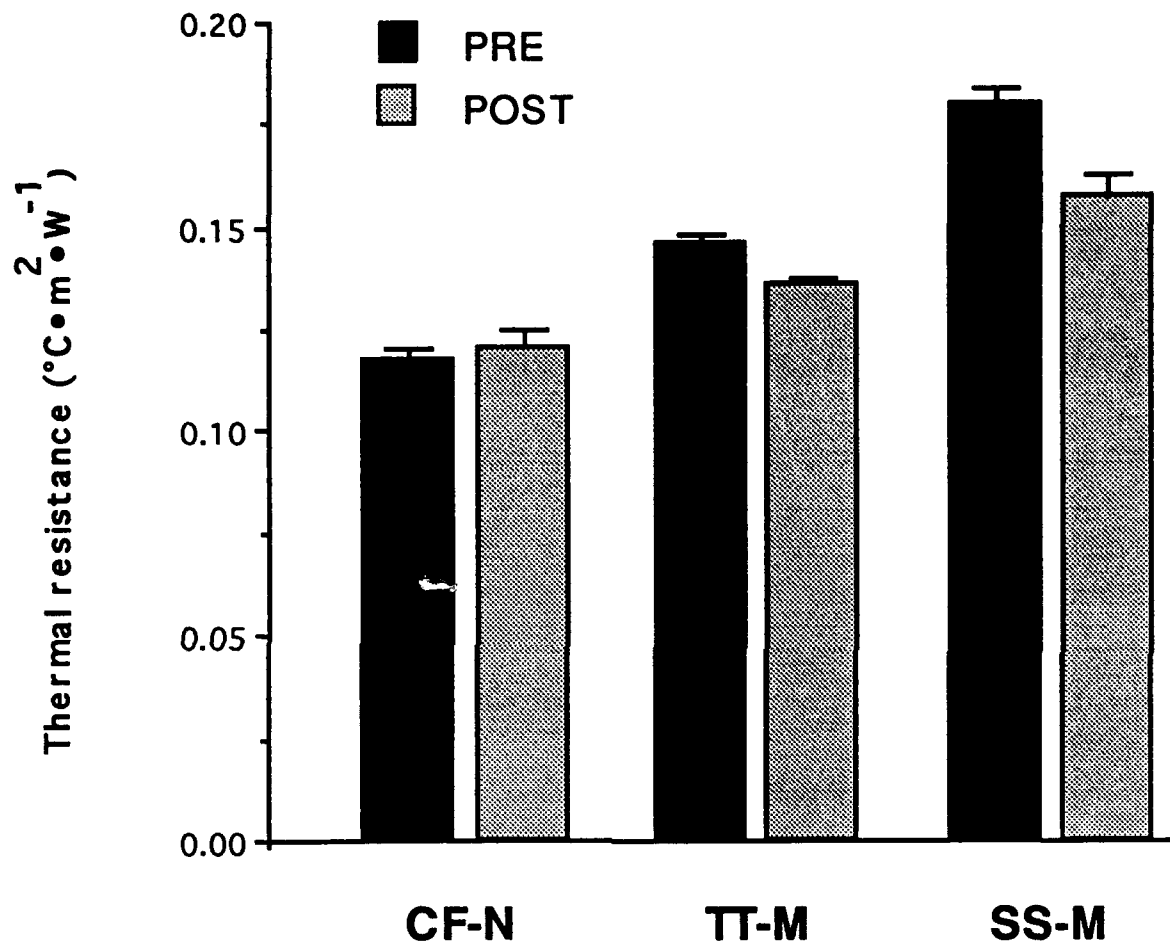


Fig.4. Thermal resistance of two thermo-metal neoprenes [titanium coated (TT-M); stainless steel coated (SS-M)] and of the current CF diving suit neoprene (CF-N) at thermal steady state in a dry environment before (PRE) and after (POST) two dive series and a six-month period. Each value is an average of two measurements (\pm SE) at different heat fluxes on the Rapid-k instrument.

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thermal resistance, diving suit, wet suit, reflective material, radiant heat