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TITLE

ANALYSIS OF THE THERMAL RESISTANCE OF SILICA FOAM

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Analysis of the Thermal Resistance of Silica Foam

by

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on behalf of:
DEPARTMENT OF NATIONAL DEFENCE

as represented by:
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EXECUTIVE SUMMARY

The thermal resistance of an experimental silica foam, when dry in air at atmospheric pressure, was measured using a custom-built apparatus. The average thermal resistance of the silica foam was 0.0253±0.0013 $m^2 \cdot K \cdot W^{-1}$. The average thickness of the foam samples was 2.48±0.31 mm. Using the average thickness and thermal resistance, the silica foam's thermal conductivity was calculated as 0.0983±0.0054 $W \cdot m^{-1} \cdot K^{-1}$.

The insulation of heavy weave Rubatex® G-231-N neoprene, the material currently used on the Canadian Forces diver's dry suit, was also measured using the same experimental apparatus. The thermal conductivity of Rubatex® G-231-N was calculated as 0.0646±0.0016 $W \cdot m^{-1} \cdot K^{-1}$. This is between 20.4 to 22.6% higher than that measured by other investigators using different equipment [1,3,4].

The thermal conductivity of both heavy and regular weave Rubatex® G-231-N was re-measured using a different heat flow measurement apparatus. The thermal conductivity of heavy and regular weave Rubatex® G-231-N neoprene was 0.0548±0.0007 and 0.0565±0.0007 $W \cdot m^{-1} \cdot K^{-1}$, respectively. These values are the same as those measured in the other studies [1,3,4]. The higher thermal conductivity measured with the custom-built apparatus is likely due to errors associated with the sample's small surface area, the method of correcting for edge heat loss and the small temperature gradient established across the materials during testing.

Unfortunately, the silica samples were not of a large enough surface area to allow for measurement of thermal conductivity using the larger, more accurate heat flow measurement device. Using the custom-built apparatus, thermal conductivity of this particular silica foam was determined to be 52% higher than that of Rubatex® G-231-N.

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INTRODUCTION

The Research Division of Mustang Survival Corporation was tasked on November 27, 1997 by the Experimental Diving Unit of the Defence and Civil Institute of Environmental Medicine (DCIEM-EDU) to measure the thermal resistance of an experimental silica foam when dry at atmospheric pressure (Requisition No. W7711-6-7329-07). No information regarding the physical properties or supplier of this particular silica foam was provided to Mustang Survival, other than sample numbers (97910-25-150 and 97910-12-150) and a date of September 10, 1997.

The apparatus used to measure the thermal resistance of the foam samples was constructed under a previous tasking (Standing Offer No. W7711-3-4411/01-XSE). In the previous tasking, thermal resistance and thickness of various commercial-of-the-shelf (COTS) neoprene foams were measured when submerged in water under hyperbaric conditions simulating depths of 0, 25, 50 and 100 meters [1]. Using the measured thermal resistance and thickness, thermal conductivity was calculated. In the present study, the silica foam was not immersed in water, nor exposed to hyperbaric conditions.

METHODS

Two samples of silica foam were received from the Experimental Diving Unit at DCIEM. A 15.5 x 15.5cm square was cut from each sample (Figure 1). Since visual examination indicated the samples had non-uniform thickness, a digital caliper (Mitutoyo Digimatic™ 500-134) was used to measure thickness eight times per sample (twice in each corner). The average density of the silica foam was calculated by weighing each sample on a digital balance (Sartorius E3000D) and dividing it by the average thickness and surface area.

The thermal resistance of the silica foam was measured with an apparatus constructed during a previous DCIEM-TIES tasking [1]. The apparatus consists of a 12.7 x 12.7 cm square, thin-film Kapton™ heating mat (Cole-Parmer H-36060) sandwiched between two 15.5 x 15.5 cm square, 0.5 mm thick copper plates (Figure 2). Waterproof double-sided adhesive tape (3M 9506024) was used to bond the heater and copper surfaces together while a neoprene adhesive (Bostik 1125A) was used to seal the exposed edges of the copper/heater/copper laminate.

The foam samples were placed on either side of the heated plates then each sample was covered with an additional copper plate. The temperature of each copper plate was measured by a Kapton™-encapsulated 100Ω platinum resistive temperature device (Instrument Service Labs S3238PA) affixed to each plate's surface. A portable data logger (Grant Instruments Squirrel 1254) was used to measure the electrical resistance of each RTD and convert it to a temperature. A constant electrical current of 159.9 mA was supplied to the 120.6Ω heater mat by a DC power supply (Lambda Model LLS5060).

The power per unit area supplied to the heater, Q (in $W \cdot m^{-2}$), can be determined by,

$$Q = I^2 R/A$$

where, I is the electrical current (in amps), R is the electrical resistance of the heater (in ohms), and A is the test surface area (in m^2).

Using the measured temperature gradient across the material on each side of the heater, the thermal resistance of each material, R_1 and R_2 (in $m^2 \cdot K \cdot W^{-1}$) can be determined as follows,

$$R_1 = 2\,(T_2 - T_1)/Q$$

$$R_2 = 2(T_3 - T_4)/Q$$

where, T_1 and T_4 are the temperatures of the outermost plates, and T_2 and T_3 are the temperatures of the heated surfaces (in C). This approach assumes that heat loss across each sample is equal.

These two thermal resistances are averaged,

$$R_a = (R_1+R_2)/2$$

and corrected by a factor that accounts for heat lost from the edges of the samples.

The measured thermal resistance, R_m, provided in this report is given by,

$$R_m = R_a/(1 - (4x/w))$$

where, x is the sample thickness and w is the sample width (in m).

Thermal conductivity, k (in $W \cdot m^{-1} \cdot K^{-1}$), is given by,

$$k = x/R_m$$

For measurement of dry thermal resistance, the apparatus was used in the same manner as the previous tasking [1]. Since the apparatus was not placed inside a hyperbaric chamber, the four RTDs were re-calibrated during this tasking to account for changes in electrical resistance due to less cabling than the previous study.

RESULTS AND DISCUSSION

The average thickness of both silica foam samples was 2.48±0.31 mm (Table 1).

Table 1 - Thickness of Silica Foam (in mm)

Sample Number – Sample Region	*Thickness*
97910-25-150 – A	2.40, 2.38
97910-25-150 – B	2.22, 2.22
97910-25-150 – C	2.80, 2.78
97910-25-150 – D	2.67, 2.67
97910-12-150 – A	2.92, 2.97
97910-12-150 – B	1.92, 1.92
97910-12-150 – C	2.56, 2.58
97910-12-150 – D	2.32, 2.32
Average:	**2.48 ± 0.31**

A – upper left hand corner
B – upper right hand corner
C – lower right hand corner
D – lower left hand corner

The average density of the silica foam was 0.826±0.045g·cm^{-3}. This density was calculated by dividing each sample's weight by its average thickness and surface area. It should be noted that this average density includes contributions from the foam's fabric backing.

Thermal resistance of the silica foam samples was measured seven times. The individual values of thermal resistance from each trial are shown in Table 2. The average thermal resistance of the silica foam was 0.0253±0.0013 m^2·K·W^{-1}.

Table 2 – Thermal Resistance of Silica Foam (m^2·K·W^{-1})

Trial No.	*Thermal Resistance*
1	0.0257 ± 0.0008
2	0.0248 ± 0.0010
3	0.0247 ± 0.0011
4	0.0260 ± 0.0011
5	0.0269 ± 0.0012
6	0.0264 ± 0.0010
7	0.0229 ± 0.0010
Average:	**0.0253 ± 0.0013**

The thermal conductivity of the silica foam was calculated from the above thermal resistance, by dividing it by the average foam thickness. The individual values of thermal conductivity from each trial are shown in Table 3. The average thermal conductivity of the silica foam was 0.0983±0.0054 W·m^{-1}·K^{-1}.

Table 3 – Thermal Conductivity of Silica Foam ($W \cdot m^{-1} \cdot K^{-1}$)

Trial No.	*Thermal Conductivity*
1	0.0966 ± 0.0033
2	0.1002 ± 0.0040
3	0.1004 ± 0.0043
4	0.0957 ± 0.0039
5	0.0923 ± 0.0039
6	0.0942 ± 0.0035
7	0.1086 ± 0.0047
Average:	**0.0983 ± 0.0054**

The thermal conductivity of heavy-weave Rubatex® G-231-N, the neoprene foam currently used for the CF Divers' dry suit, was measured as 0.065±0.001 $W \cdot m^{-1} \cdot K^{-1}$ using the custom-built apparatus. When this insulation was measured previously using a different heat flow measurement apparatus (Foundation HFMA-1), average thermal conductivity was 0.054±0.003 $W \cdot m^{-1} \cdot K^{-1}$ [1]. For this particular neoprene, thermal conductivity measured by the custom-built apparatus is 22% higher than that measured with HFMA-1. HFMA-1 is considered more accurate than the custom-built apparatus, as it is calibrated annually to traceable reference insulation samples supplied by the National Research Council [2], has a larger test surface area, and restricts heat loss from the sample's edges.

The thermal conductivity of 0.054±0.003 $W \cdot m^{-1} \cdot K^{-1}$, previously measured for Rubatex G-231-N with the HFMA-1, agrees well with values measured by other investigators using different methods [3,4]. Ducharme and Frim of DCIEM [3] measured a dry thermal resistance of 0.120 $m^2 \cdot K \cdot W^{-1}$ from a 6.4mm thick sample of G231N–heavy weave. This equates to a thermal conductivity of 0.053 $W \cdot m^{-1} \cdot K^{-1}$. Romet of DCIEM [4] measured a dry thermal resistance of 0.1327 $m^2 \cdot K \cdot W^{-1}$ from 7.1mm G231-N. This equates to a thermal conductivity of 0.054 $W \cdot m^{-1} \cdot K^{-1}$.

Table 4 contains the thermal conductivity of the silica foam and three other COTS neoprene foams measured using both the HFMA and the custom apparatus. The value in brackets in the right-hand column of Table 4 represents the difference in thermal conductivity measured with the custom apparatus, expressed as a percentage of thermal conductivity measured with the HFMA-1. The custom-built apparatus gives a thermal conductivity that is 7 to 25% greater than that measured with HFMA-1.

Table 4 - Thermal Conductivity of various COTS Insulating Foams (in W·m^{-1}·K^{-1})

Material	*Thermal Conductivity Using HFMA-1*	*Thermal Conductivity using custom apparatus*
Silica foam	Insufficient sample surface area	0.098 ± 0.005
Rubatex® G-231-N–heavy weave	0.054 ± 0.003	0.065 ± 0.001 (+20.4%)
Rubatex® G-231-N–reg. Weave	0.058 ± 0.003	0.062 ± 0.001 (+6.9%)
Yamamoto Ti-α-reg. Weave	0.048 ± 0.002**	0.060 ± 0.001 (+25.0%)

** Value measured in previous tasking W7711-3-4411/01-XSE [1].

The thickness, thermal resistance and thermal conductivity of the silica foam were recently measured by Randall Osczevski of DCIEM [5]. Osczevski measured the insulation of one particular sample of silica foam three times and that of another sample two times. Their average thickness for the two silica foam samples was 2.15 ± 0.08 mm. Their average thermal resistance and conductivity were 0.0274 ± 0.0040 m^2·K·W^{-1} and 0.0793 ± 0.0083 W·m^{-1}·K^{-1}, respectively.

Osczevski suspects the values of thermal conductivity may be about 10% too low (Appendix A). If true, his average thermal conductivity should be approximately 0.0872 W·m^{-1}·K^{-1}. A comparison of values from the custom-built apparatus and HFMA suggests our thermal conductivity values may be as much as 25% too high. Decreasing the average thermal conductivity of silica foam, as measured in this study, by 25% would give a thermal conductivity of 0.0786 W·m^{-1}·K^{-1}, which is nearly equal to the non-corrected, original value measured by Osczevski [5].

This study found the thermal conductivity of silica foam to be higher than that of heavy-weave Rubatex® G-231-N by 51% (0.098 versus 0.065 W·m^{-1}·K^{-1}) and regular-weave Yamamoto Ti-α by 63% (0.098 versus 0.060 W·m^{-1}·K^{-1}). If silica foam is to achieve the same thermal resistance as COTS neoprene foams, it will be greater in thickness than the COTS neoprene. It is speculated that silica foam has a greater compressional resistance than most neoprenes. It is likely that at some unknown water depth, insulation levels from silica and neoprene would converge and become the same. Using less compressive insulation in a diving suit may offer an advantage in terms of pre-dive comfort. The non-compressed thickness of insulation required to achieve a given level of insulation at extreme depths may be less with silica foam than with COTS neoprene.

CONCLUSION

The average thickness of the silica foam samples was 2.48±0.31 mm. The average density of the silica foam was $0.826\pm0.045 g\cdot cm^{-3}$. The average thermal resistance of the silica foam was $0.0253\pm0.0013\ m^2\cdot K\cdot W^{-1}$. This equates to an average thermal conductivity for the silica foam of $0.0983 \pm 0.0054\ W\cdot m^{-1}\cdot K^{-1}$.

This study found the thermal conductivity of this particular silica foam to be higher than that of COTS neoprenes. The thermal conductivity of the silica foam is greater than that of heavy-weave Rubatex® G-231-N by 51% (0.098 versus 0.065 $W\cdot m^{-1}\cdot K^{-1}$) and regular-weave Yamamoto Ti-α by 63% (0.098 versus 0.060 $W\cdot m^{-1}\cdot K^{-1}$).

Changes to custom-built apparatus would be necessary in order to improve its accuracy. It is recommended that future measurements of dry thermal insulation be conducted in the HFMA-1. This requires a minimum sample size of 61x61cm.

The custom-built apparatus should be considered a valuable tool in measuring thermal insulation of foam materials when immersed in hyperbaric conditions. Its use allows for assessment of relative differences in thermal insulation provided by different materials, as opposed to providing highly accurate, absolute measurements.

REFERENCES

1. Uglene, W., and Nistuk, R., *Analysis of the Thermal Insulation of Metallized Neoprene Foam*, M.E.T.A. Research Inc. report submitted to DCIEM, Contract No: W7711-3-4411/01-XSE, March 1996.
2. National Research Council, *Reference Insulation Samples: NRC 374-182-15/18.*
3. Ducharme, M., and Frim, J., *Evaluation of Two Thermo-metal Neoprenes*, Sixth International Conference on Environmental Ergonomics, 1994, p 66-67.
4. Romet, T.T., *Thermal insulation in various dry and flooded dry suit/pile combinations*, Proceedings of the DCIEM Diver Thermal Protection Workshop, pp. 75–80, 1989.
5. Osczevski, R. and Eaton, D., Personal correspondence, March 1998.

APPENDIX A – DCIEM measurements of Silica Foam [5]

Data for Dave Eaton

Upper plate 17 °C, lower plate 15 °C.					
Sample ID	k [W/mK]	Thickness [m]	R [m2K/W]	R [clo]	Mass of sample
-12-	0.0688	0.00227	0.033	0.213	108 g
-12-	0.0723	0.0022	0.030	0.196	
-25-	0.0839	0.00214	0.026	0.165	118 g
-25-	0.0836	0.00211	0.025	0.163	
-25-	0.0879	0.00203	0.023	0.149	
measured for comparison:					
Air	0.0302	0.00204	0.068	0.436	negligible
Printer Paper	0.053	0.00204	0.038	0.248	92 g
[21 sheets]	0.0523	0.00201	0.038	0.248	
Blue foam pad	0.036				
of closed cells					
I suspect these values of k may be about 10% too low.					
The apparatus isn't calibrated for very thin samples.					
RJO 16/10/97					

FIGURES

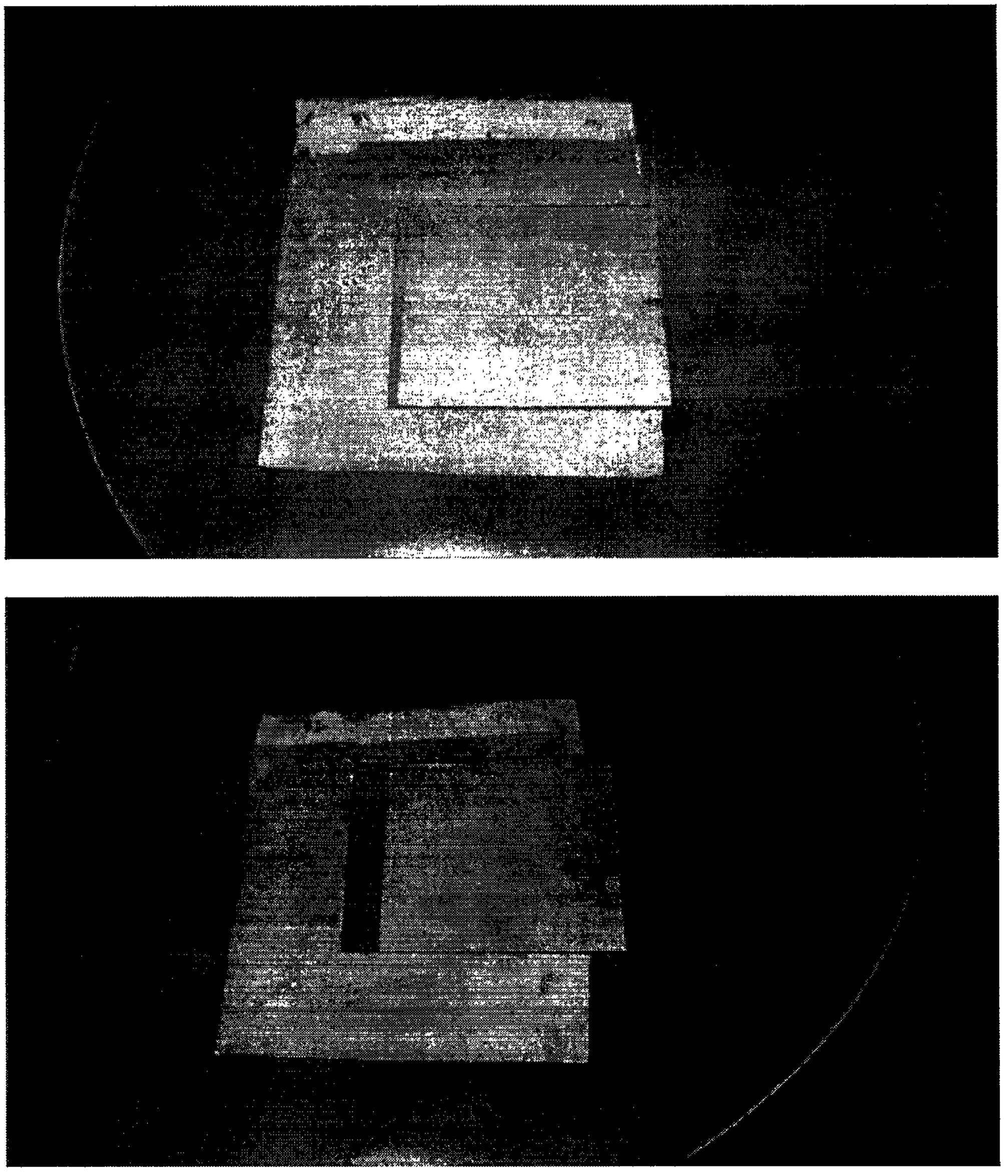

Figure 1 – Original Samples and Test Specimens

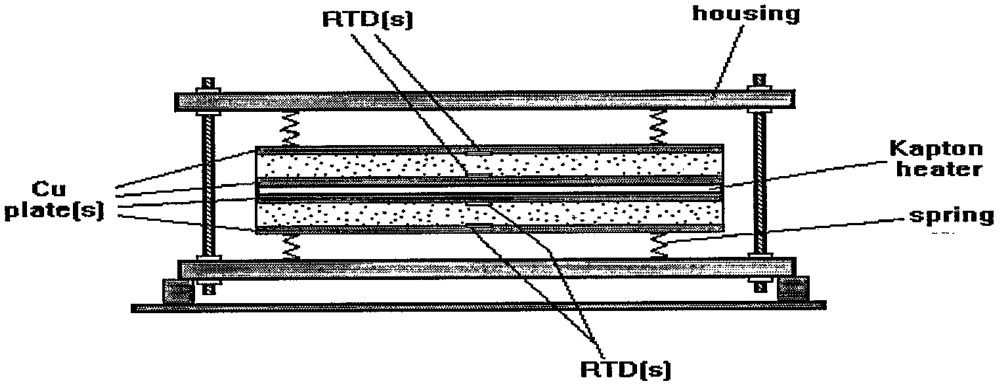

Figure 2 – Custom-built apparatus

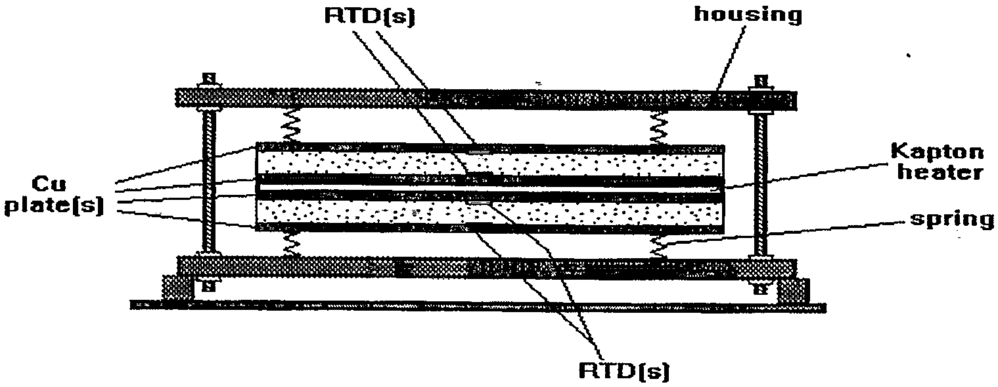

Figure 2 – Custom-built apparatus

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