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THERMAL PROTECTION OF COMMERCIAL DRY SUIT DIVING SYSTEMS

US ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

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Total insulation values of seven commercial variable volume dry diving suits, and of four of these suits worn in combination with various commercial and Navy insulating undergarments, were measured on an electrically heated copper man standing in air or immersed to the neck in water. Values in air ranged from 1.27 clo to 1.92 clo for the suits alone, and from 1.89 to 2.67 clo for the suit-undergarment combinations. These values decreased by from 0.73 clo to 1.29 clo in water, of which 0.66 clo represented reduction in the amount of film insulation at the suit surface Block 20, with immersion (0.84 clo in air →

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versus 0.18 clo in water); the remainder represented decreased intrinsic insulation of the ensemble due to water pressure. Extension of these results to a diver working in water (metabolic rate M = 400 watts) indicated that none of the combinations would protect adequately for two hours at 0°C, although four were adequate at 5°C and above. However, these combinations would cause serious overheating after two hours of moderate activity (M = 200 watts) in air at 15°C or below unless the suit was unzipped or hood and gloves removed to increase cooling.

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Technical Report

No. T 1/81

Thermal Protection of Commercial Dry Suit Diving Systems

by

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ABSTRACT

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Introduction

USARIEM's unique capabilities to obtain direct measurements of the thermal insulation characteristics of protective clothing systems, including immersion suits, and to extrapolate such characteristics to the physiological responses of men wearing these systems, was made available to the Naval Coastal Systems Center, Panama City, Florida under a Military Interagency Purchase Request. USARIEM's interest in such studies stems from related questions on protection for Army Air Crew flights over water, for Navy "Seal" teams and for riverine and swamp crossing operations. This report details the equipment and techniques used and the results of these investigations on a number of commercially available variable volume dry diving suits.

Materials and Methods

The copper manikin used for the Navy dry suit tests is a life-sized, anthropomorphic copper shell, wired internally and supplied by a control unit with electric (AC) power for heating. The entire surface of the man's copper shell was coated with a rubber-based, adhesive compound for waterproofing.

Skin temperatures are recorded from twenty-one thermocouples located in the manikin shell. These are distributed over the skin surface, from the top of the head to the insteps of the feet, as shown in Figure 1. A series of ten thermistor sensors, also imbedded in the copper shell, are connected to an on-off type electronic controller which maintains the skin temperature at any preselected level between 15 and 40°C. Two cables, one for heating power and the other containing thermistor and thermocouple leads, are brought out of the manikin through the eye sockets.

Adjustment of the power level to the manikin is made through an autotransformer in the instrument console. This autotransformer is set to provide power in excess of the watts of heat dissipated to the surroundings, at a

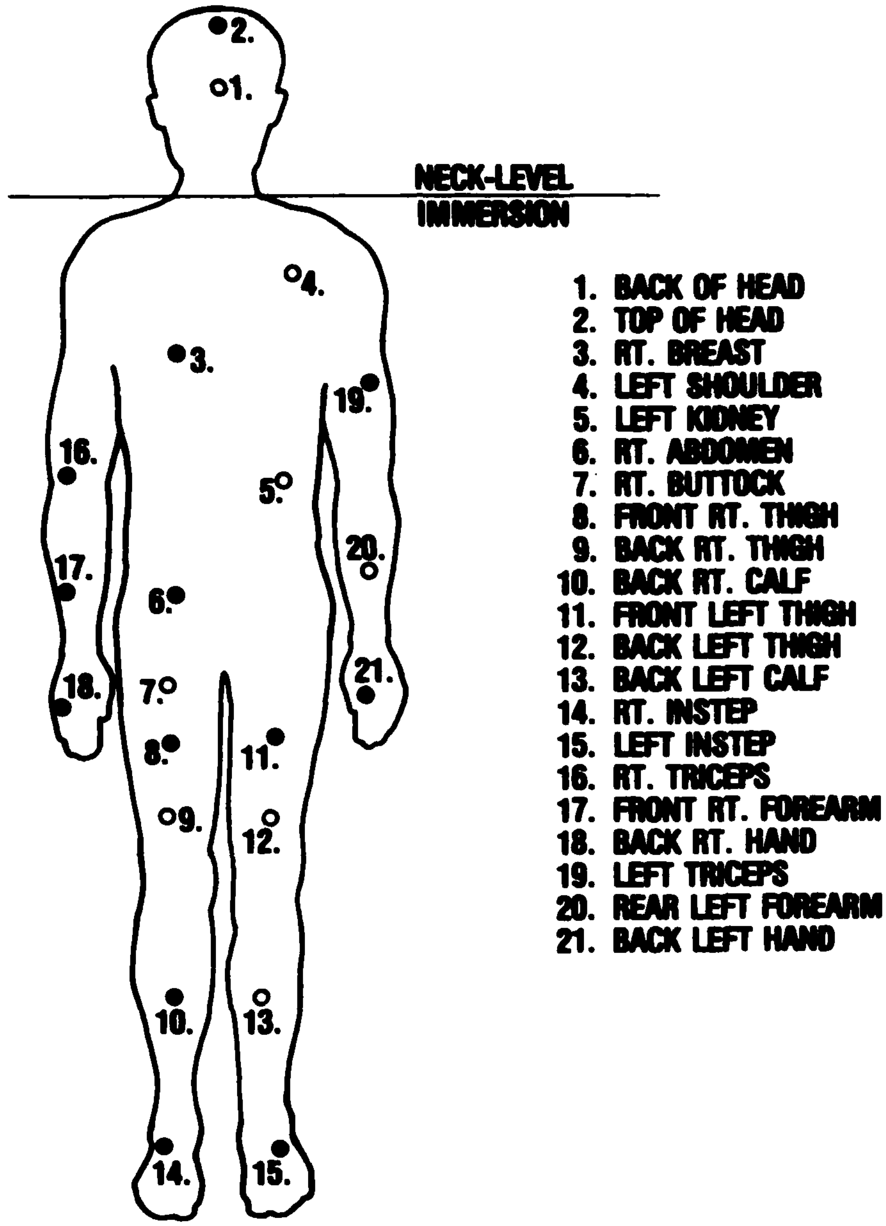

Figure 1. Location of thermocouple sensors on manikin surface

level so that the temperature control relay is closed (i.e., delivering power) for from 30 to 70% of the time; the relay cycles on and off every few minutes, holding the individual manikin temperatures constant within $\pm 0.7^{\circ}C$ and the mean surface temperature constant within $\pm 0.5^{\circ}C$. Average rate of power input to the manikin is determined by multiplying readings of circuit amperage and voltage, averaged over the entire test period, by the relay time factor, i.e., the percentage of time the power relay is closed. This factor is calculated from the readings of two timers; one records the total run time, the other the time that power is demanded during that run. Since the long-term manikin temperature is not changing, this average rate of power input is taken as equal to the average rate of heat loss from the manikin, through the clothing, to the environment.

Insulation values of seven different commercial dry suits were determined with the manikin standing either in "still" air (approximately 0.1 m/s air motion) or immersed to the neck in water. Four of these suits were also studied in combination with various commercial and Navy insulating undergarments. Finally, insulation values in air were obtained on the undergarment items alone.

The dry suits and undergarments used in the study are listed below. A more complete description of these items is given in Appendix A.

Suits:*

a. Poseidon Unisuit

b. Viking Suit w/Hood

c. O'Neill Supersuit w/Hood

d. White Stag Suit

e. Bayley Aquastatic Suit

f. Imperial Suit

g. Sub Aquatic Systems Suit w/Hood

Undergarments:

h. Arctic Explorer (Poseidon)

i. Grey Foam (Viking)

j. Benthos II (O'Neill)

k. Neoprene "Shorty" (White Stag)

l. Navy Waffle

m. Navy Spacer Garment

*Use of commercial, named items in no way represents any endorsement of either these items or the suppliers; items tested were those readily available "off the shelf".

One set of mitts (3/16" nylon-lined foam neoprene) was used for all suit or suit/undergarment combinations in air and water; the individual mitts supplied with some of the suits generally could not be used on the copper man's hands and, in addition, would have introduced an unnecessary confounding factor if used to evaluate these suits. Water was allowed to enter the mitts in all immersion conditions.

The manikin was secured in an upright position, standing on a foam pad on an aluminum channel platform suspended by steel cables connected to an electric hoist. For measurements in air, the platform was positioned ~0.2 m above the water surface of the immersion tank, a square pool four meters deep which holds approximately 34 m^3 of water. For immersion measurements, the manikin was simply lowered into the water to about 2 cm below the neck joint.

In the water immersion studies, the suits and suit/undergarment combinations were run both deflated and inflated with low pressure air. Air was supplied via the oral inflation hose in the suit for all immersed-inflated conditions. In all cases, leakage of air out of the suit made it necessary to constantly add air into the suit to maintain inflation. Air leaked from the suit either by entering the manikin through the unsealed neck joint and leaving through the cable openings in the eye sockets or escaped via the neck seal area between the suit and manikin. The latter was difficult to control because of the inaccessibility of the neck area under the suit, the nature of the joint, and the neck configuration. In one case (the Viking suit) air leakage occurred through a face seal which, on the copper man, could not retain the air. The tendency for air to rise in all suits was increased because of the head-out condition of the immersion tests; with the man oriented vertically, the air-water pressure gradient caused air to be driven up into the shoulder-neck area of each suit. There was no apparent inflation below the abdomen. In addition, streams of small bubbles were observed being emitted from zippers, seams, and in some suits, through the neoprene material itself during inflation. Air flow to maintain inflation ranged from 0.1 L/min to 1.5 L/min.

For all inflated conditions the convectional heat loss afforded by these air flows into and through the suit would tend to yield measured insulation (clo) values slightly below the true values. However, air pockets existed, in varying degree, in the shoulder area in most suits during inflated runs; these would tend to increase clo values slightly because the shoulder areas of the suits were thus exposed in air instead of in water. Therefore, the average increase of 0.04 clo from the deflated to the inflated suit condition may not indicate the true total increase in insulation brought about by suit inflation. Trapped moisture in a suit appeared generally to have little effect on the clo determination; those runs where considerable water leakage occurred were re-run after drying out the suit but, generally, only small changes in insulation value were found.

The suit insulation value immersed was determined first in an inflated condition; then the suit was allowed to deflate and the deflated suit clo value was determined after a one hour equilibration period. These two conditions (inflated and deflated) were measured in water on the same day for a given ensemble, usually on the day after the insulation in air had been determined.

The air inflation displaced ~0.007 m^3 (0.24 ft^3) of water, representing a positive buoyancy of ~6.8 kg (15 lbs). A 15 lb (6.8 kg) lead-weight belt was used on the manikin during all immersion conditions, whether inflated or deflated; although required only during the inflation phase, this allowed the system to remain otherwise undisturbed between the inflation phase measurements and the subsequent deflation phase. A test run was made without the belt during a deflated immersion of one suit (the Imperial Suit); the difference in insulation was negligible; 0.94 clo w/belt, 0.95 clo w/o belt.

The average water pressure on the man, with the feet at 1.5m depth, was ~60 torr; compression of 1/4" foam neoprene by that pressure causes an insulation loss $\leq$ 2%. Some variability existed in suit fit; fit was snug for all suits from feet to hips, with varying degrees of looseness in the torso especially at the back, upper arms and shoulders. Also, outer garments tended to compress undergarments, especially in the case of the Unisuit over the Arctic Explorer undergarment, reducing the loft of the latter.

The manikin was controlled at a mean skin temperature around 32.5°C for the insulation measurements in air. However, because of the greater heat loss, in water the power limitations of the manikin (maximum of about 500 watts with 120 volts applied) usually required selection of a slightly lower mean surface temperature to maintain satisfactory temperature control, i.e., to limit the relay timing factor to 80% or less. Mean skin temperatures for the immersion runs ranged from 27.8°C to 32.6°C depending on the insulating effectiveness of the system being measured. In air, mean skin temperature was calculated as the simple average of readings from the 21 thermocouples distributed over the manikin surface. Ambient temperature, in air or water, was recorded as the average of four fixed thermocouples placed in close proximity to the manikin at hip level. After allowing time for thermal equilibrium to be established (three hours for air runs and about two hours for water immersion runs after initial warmup), data (temperatures, amperes, volts, time factors) were collected during three separate 30-minute periods; in each, three sets of skin and ambient temperature data, and the associated amperage and voltage levels on the man were recorded; the relay time factor was also determined at the end of the period. A separate insulation (clo) value was calculated for each half-hour period after averaging the three sets of readings. In turn, the three insulation (clo) values from the three 30-minute periods were averaged to obtain a mean clo value for that clothing ensemble condition. Differences between the three successive values generally were 0.1 clo or less in air, and were even smaller in water; larger differences were investigated by additional measurements or re-runs.

Insulation, in clo units (where 1 clo = $0.155^{o}C\ m^2$/watt), was calculated for all air exposures, with the heat loss from the head included, as:

$$\text{Insulation (clo)} = \frac{(\bar{T}_s - \bar{T}_a)(1.90)}{(E)(I)(T.F.)(0.155)}$$

where: T_s = mean (21 points) skin temperature (^{o}C)

T_a = mean air temperature (^{o}C)

1.90 = surface area of manikin (m^2)

E = voltage supplied (V)

I = current drawn (A)

T.F. = time factor = $\frac{\text{Power "on" time}}{\text{total time}}$ (%)

In all the insulation measurements in water the man was immersed only to the neck. Because the head was not immersed, the two measured head skin temperatures were subsequently omitted from the calculation of mean skin temperature and the total surface area value of the man (1.90 m^2) was reduced by the area of the head (0.152 m^2); that fraction of total power to the man that supplied the head segment was also subtracted. The fraction of total power supplied the body during immersion conditions was calculated from data obtained from a single run made on the nude manikin, immersed to neck level in water, while head and air temperatures, current, voltage, and time factors were recorded. This fraction is given by the expression;

$$1 - \frac{\text{head watts}}{(\text{instantaneous watts})(\text{T.F.})}$$

A value for head watts was derived based on the assumption that the air insulation around the head was 0.8 clo. Accordingly,

$$\text{Head watts} = \frac{(\text{T head} - \text{T air})(0.152)}{0.8\,(0.155)}$$

where 0.152 is the head surface area and the factor 0.155 is the clo conversion factor $\left(1 \text{ clo} = 0.155 \frac{{}^{\circ}\text{C m}^2}{\text{watt}}\right)$.

During the nude run used to establish a standard value to discount heat loss from the head, head temperature averaged 26.02°C, air temperature was 11.01°C, instantaneous manikin watts (E x I) averaged 498.2, and the time factor measured 60.73%. From these data, head watts were 18.40 and therefore the percent power to the manikin, exclusive of the head, was:

$$1 - \frac{18.40}{(498.2)(.6073)}$$

or 94%. This percentage was used in calculating the insulation values for all water immersion measurements and for calculating "w/o head" clo values for the various dry suit combinations in air. The equation for calculating "body" clo (head excluded) was:

$$\text{clo} = \frac{(\bar{T}_s - T_a)(1.748)}{0.94(E)(I)(T.F.)(0.155)}$$

where T_s = mean skin temperature without including the head (average of 19 thermocouples), °C

T_a = mean air or water temperature, °C

1.748 = surface area, manikin minus head, m^2

Results and Discussion

The data and insulation (clo) values are summarized in the following three Tables:

Table I presents the mean manikin skin temperatures, with and without the head section included in the calculations, measured during the tests of the 22 different ensembles as well as the nude manikin in air, and the ambient air temperatures.

Table II presents the mean skin temperatures, excluding the head, with the suit inflated and deflated, and the associated water temperatures for 17 protective ensembles and for the nude man measured in water.

Table III presents the insulation (clo) values in air, with and without the head section included, and in water, excluding the head section, with and without inflation.

TABLE I

MEASUREMENTS IN AIR
MEAN SKIN AND AMBIENT TEMPERATURES
(°C)

SUIT AND/OR UNDERGARMENT	w/ head $\bar{T}_s$	w/o head $\bar{T}_s$	T_a
Outergarment Only:			
1. Unisuit	32.6	32.7	21.7
2. Viking	32.4	32.4	23.0
3. O'Neill Supersuit	32.2	32.0	24.0
4. White Stag	32.4	32.2	25.2
5. Bayley Aquastatic	32.7	32.5	23.2
6. Imperial	32.6	32.4	22.3
7. Sub Aquatic Systems	32.5	32.3	25.3
Ensemble:			
8. Unisuit w/Arctic Explorer Undergarment	32.2	32.3	22.4
9. Viking w/Viking Undergarment	32.6	32.8	22.7
10. O'Neill Supersuit w/Benthos II Undergarment	32.7	32.7	21.9
11. White Stag w/Neoprene Shorty Undergarment	32.5	32.3	23.9
12. Unisuit w/2 sets Arctic Explorer Undergarments	32.5	32.6	25.8
13. Viking w/Benthos II Undergarment	32.4	32.5	23.2
14. Unisuit w/Viking Undergarment	32.6	32.8	23.1
15. O'Neill Supersuit w/Navy Waffle Undergarment	32.2	32.1	21.8
16. Unisuit w/Spacer Leggings	32.4	32.5	23.3
17. O'Neill Supersuit w/Spacer Leggings	32.3	32.3	24.7
Undergarment Only:			
18. Viking Undergarment	32.5	32.7	23.0
19. Arctic Explorer Undergarment	32.1	32.4	22.0
20. Arctic Explorer Undergarment (2 sets)	32.4	32.7	24.4
21. O'Neill Benthos II Undergarment	32.9	33.2	22.3
22. Navy Waffle Undergarment	32.7	32.7	22.7
23. Nude Manikin	32.4	32.2	23.3

TABLE II

MEASUREMENTS IN WATER
MEAN SKIN AND AMBIENT TEMPERATURES
(°C)

SUIT OR ENSEMBLE	Inflated w/o Head $\bar{T}_s$	Inflated w/o Head T_w	Deflated w/o Head $\bar{T}_s$	Deflated w/o Head T_w
<u>Outgarment Only:</u>				
1. Unisuit	31.9	13.9	31.9	14.0
2. Viking	22.5	14.0	22.7	14.1
3. O'Neill Supersuit	28.3	14.1	28.4	14.2
4. White Stag	--	--	28.8	14.2
5. Bayley Aquastatic	--	--	--	--
6. Imperial	28.4	14.3	28.5	14.2
7. Sub Aquatic Systems	27.8	14.2	27.8	14.4
<u>Ensemble:</u>				
8. Unisuit w/Arctic Explorer Undergarment	31.8	14.2	31.8	14.3
9. Viking w/Viking Undergarment	30.4	13.9	30.3	14.0
10. O'Neill Supersuit w/Benthos II Undergarment	31.3	13.9	31.3	14.0
11. White Stag w/Neoprene Shorty Undergarment	--	--	30.4	14.2
12. Unisuit w/2 sets Arctic Explorer Undergarments	31.8	14.2	31.7	14.3
13. Viking w/Benthos II Undergarment	30.0	13.8	29.8	13.9
14. Unisuit w/Viking Undergarment	31.1	13.8	31.3	14.0
15. O'Neill Supersuit w/Navy Waffle Undergarment	29.9	14.4	29.9	14.5
16. Unisuit w/Spacer Leggings	32.6	13.9	32.5	13.7
17. O'Neill Supersuit w/Spacer Leggings	32.0	14.0	32.1	14.1
18. Nude Manikin	--	--	26.0	21.6

TABLE III

Total Insulation (clo) Values

SUIT AND/OR UNDERGARMENT	Air Clo w/ Head	Air Clo w/o Head	Water Clo w/o Head Inflated	Water Clo w/o Head Deflated
Outer Garment Only:				
1. Unisuit	1.95	1.92	0.94	0.91
2. Viking	1.30	1.27	0.38 [1]	0.35 [1]
3. O'Neill Supersuit	1.73	1.66	0.89	0.85
4. White Stag	1.84	1.74	N.A. [2]	0.96
5. Bayley Aquastatic	1.86	1.78	N.A. [3]	N.A. [3]
6. Imperial	1.92	1.86	0.95 [1]	0.94 [1]
7. Sub Aquatic Systems	1.61	1.53	0.80	0.77
Ensemble:				
8. Unisuit w/Arctic Explorer Undergarment	2.45	2.44	1.38	1.34
9. Viking w/Viking Undergarment	2.10	2.10	1.00	0.87
10. O'Neill Supersuit w/Benthos II Undergarment	2.37	2.33	1.33	1.27
11. White Stag w/Neoprene Shorty Undergarment	2.08	2.00	N.A. [2]	1.11
12. Unisuit w/2 sets Arctic Explorer Undergarments	2.48	2.48	1.55	1.55
13. Viking w/Benthos II Undergarment	1.93	1.92	0.85 [4]	0.73 [4]
14. Unisuit w/Viking Undergarment	2.68	2.67	1.38	1.38
15. O'Neill Supersuit w/Navy Waffle Undergarment	1.95	1.89	0.98 [5]	0.96 [5]
16. Unisuit w/Spacer Leggings	2.07	2.05	1.17	1.13
17. O'Neill Supersuit w/Spacer Leggings	2.06	2.01	1.12	1.07
Undergarment Only:				
18. Viking Undergarment	1.89	1.89	--	--
19. Arctic Explorer Undergarment	1.95	1.96	--	--
20. Arctic Explorer Undergarment (2 sets)	2.34	2.39	--	--
21. O'Neill Benthos II Undergarment	2.27	2.29	--	--
22. Navy Waffle Undergarment	1.17	1.15	--	--
23. Nude Manikin [6]	0.88	0.84	--	0.18

1. Moisture in boots (clo slightly low)
2. Neck seal could not be accomplished
3. Suit had too many leaks for "dry" run
4. Moisture in left leg and abdomen area (clo probably low)
5. Left arm wet to elbow (clo probably good value)
6. The coating used to waterproof the manikin can be estimated to provide ~ 0.13 clo during water immersion.

The effects of water immersion on insulation values of the various dry suit combinations in Table III may best be seen by comparing the "w/o head" values in air and water. To simplify discussion of these effects, only the inflated suit values will be used for the comparisons; the values with suits deflated might equally well have been chosen without changing any of the conclusions since these values were consistently lower than inflated suit values, by from 0.03 to 0.05 clo, except in a few cases.

Reductions in clo value with water immersion range from 0.73 to 1.29 clo, as shown in Table IV. Most of the reduction for each suit occurs because the insulation of the water film on the suit surface is much lower than the corresponding air film insulation during air exposure. From the results on the nude manikin (system 23) these boundary layer insulations, which include the manikin waterproof coating and are included in the Table III values, appear to be 0.84 and 0.18 clo for air and water, respectively. Thus, one would expect water immersion to reduce insulation by 0.66 clo (0.84-0.18) even if the suits were rigid and unaffected by water pressure. Any larger reduction with water immersion may be presumed to reflect a reduction in the insulation of the suit or suit/undergarment itself. For most combinations, the total reductions were less than 1.0 clo, corresponding to losses of 0.34 clo or less in intrinsic suit insulation. These losses are due to (1) reduction in thickness of air spaces between the suit and manikin, or between the suit and undergarment, as external water pressure collapses the suit and/or (2) slight compression of the insulation in the suit or undergarment due to water pressure (0.75 meter average pressure head in this study). The external dimensional changes in the suits must have been small since a 1/8" thick air layer provides more than 0.34 clo of insulation. Only systems 8, 9, 13, and 14 lost more than 1 clo of total insulation in water. System 14, the Unisuit with Viking foam, lost the most (1.29 clo) but it is unclear how much of this reduction was due to air space reduction and how much to compression of the open cell foam in the undergarment.

TABLE IV

LOSS OF INSULATION DUE TO WATER IMMERSION; INTRINSIC INSULATIONS IN AIR AND WATER. (clo units)

SUIT AND/OR UNDERGARMENT	Decreased Total Insulation In Water	Intrinsic Insulation In Air	Intrinsic Insulation In Water	Intrinsic Insulation Loss In Water
Outer Garment Only:				
1. Unisuit	0.98	1.08	0.76	0.32
2. Viking	0.89	0.43	0.20	0.23
3. O'Neill Supersuit	0.77	0.82	0.71	0.11
4. White Stag	0.78 [1]	0.90	0.78 [1]	0.12
5. Bayley Aquastatic	—	0.94	--	--
6. Imperial	0.91	1.02	0.77	0.25
7. Sub Aquatic Systems	0.73	0.69	0.62	0.07
Ensemble:				
8. Unisuit w/Arctic Explorer Undergarment	1.06	1.60	1.20	0.40
9. Viking w/Viking Undergarment	1.10	1.26	0.82	0.44
10. O'Neill Supersuit w/Benthos II Undergarment	1.00	1.49	1.15	0.34
11. White Stag w/Neoprene Shorty Undergarment	0.89 [1]	1.16	0.93 [1]	0.23
12. Unisuit w/2 Sets Arctic Explorer Undergarments	0.93	1.64	1.37	0.27
13. Viking w/Benthos II Undergarment	1.07	1.08	0.67	0.41
14. Unisuit w/Viking Undergarment	1.29	1.83	1.20	0.63
15. O'Neill Supersuit w/Navy Waffle Undergarment	0.91	1.05	0.80	0.25
16. Unisuit w/Spacer Leggings	0.88	1.21	0.99	0.22
17. O'Neill Supersuit w/Spacer Leggings	0.89	1.17	0.94	0.23

1. Based on value for deflated suit in water.

The Unisuit alone (system 1) fit the manikin rather loosely, and the 0.98 clo total insulation loss (intrinsic insulation loss of 0.32 clo) in water was most likely due to reduced thickness of the air spaces between the suit and manikin, i.e., collapse of the suit under water pressure. However, the fit would improve with the foam undergarment under the suit, (system 14) and compression of the foam would better explain the insulation decrease in water (1.29 clo reduction in total insulation, and 0.63 clo loss of intrinsic insulation). System 9, also using the Viking foam undergarment, lost 1.10 clo total insulation and 0.44 clo intrinsic insulation in water. This analysis is inconclusive, however, since the fiberfilled Benthos II undergarment probably is more easily compressed than the Viking foam, but systems using the Benthos II garment (10 and 13) showed less effects of compression (1.00 and 1.07 clo losses in total insulation in water) than the systems with Viking foam (9 and 14).

An analysis of the insulating effectiveness of the Viking, Arctic Explorer, and O'Neill Benthos II undergarments, based on the results in Table III, is provided in Table V.

TABLE V

EFFECTIVE INSULATING VALUES OF UNDERGARMENTS WITH AND WITHOUT DRY SUIT (clo units)

	Systems[1]	In Air	In Water
Viking Undergarment	18-23	1.05	---
Under Unisuit	14-1	0.75	0.44
Under Viking	9-2	0.83	0.68
Arctic Explorer Undergarment (2 Sets)	20-23	1.55	---
Under Unisuit	12-1	0.56	0.61
O'Neill Benthos II Undergarment	21-23	1.45	---
Under Viking	13-2	0.65	0.47
Under O'Neill Supersuit	10-3	0.67	0.44

1. Table values obtained by subtracting second system value from first system value. Value for undergarment alone was obtained by subtracting nude air clo value of 0.84 (system 23).

In air, the Viking open cell foam undergarment increased the insulating clo value the most, by 0.75 clo under the Unisuit and by 0.83 clo under the Viking suit. The Benthos II undergarment ranked second (0.65 and 0.67 clo increases) and two sets of Arctic Explorer undergarments third (0.56 clo). It will be seen that these insulation increases bear little relationship to the intrinsic insulation values of the undergarments alone. The Viking had the least insulation (1.05 clo) but was first in effectiveness when placed under a dry suit; the best undergarment alone, 2 sets of Arctic Explorers, showed up worst under a suit. This lack of correlation may be partly a function of suit fit; a tight suit would compress an undergarment more than a loose one and render the undergarment less effective. However, the Viking and Arctic Explorer undergarments were both measured under the same suit (Unisuit), leading one to suspect that the poor correlation is more a function of the ease of compression of the undergarment. The Viking appears to be a thinner undergarment, based on its lower clo value when used alone (1.05 clo vs 1.55 clo for 2 sets of Arctic Explorer). However, the Viking apparently resisted suit compression better and hence provided more insulation in the suit/undergarment system than the 2 sets of Arctic Explorer undergarments.

In water (inflated suit), the Viking undergarment lost its advantage when worn under the Unisuit; water pressure appeared to drop its effective value from 0.75 to 0.44 clo, but had no effect on the contribution of the two sets of Arctic Explorer undergarments; indeed, an insignificant increase of 0.05 clo was observed. This inconsistency is not easily explained but may have been due to differences in suit inflation or some uncontrolled dressing variable. The Viking underwear showed up better under the Viking suit, dropping only to 0.68 clo.

Estimates for recommending upper environmental limits for the dry suits or suit/undergarment configurations in air may be made by manipulation of the basic heat transfer equation:

$$I = \frac{6.46(T_s - T_a)(A)}{H_s}$$

where I = intrinsic insulation of clothing (I_{cl}) plus surface air layer (I_A), clo units

T_s = mean skin temperature, ^oC

T_a = air temperature, ^oC

A = nude body surface area, m^2

H_s = rate of heat loss from body surface, W

Rewriting this expression to solve for T_a gives:

$$T_a = T_s - \frac{H_s I}{6.46A}$$

Essentially, this equation indicates the ambient temperature at which the rate of heat loss through a suit with I clo units of insulation will be H_s. In order to achieve thermal balance for the diver, H_s should equal his metabolic heat production less his sensible respiratory and evaporative losses.

Some departure from this ideal case is permissible in specifying an upper temperature limit for pre-immersion activity in the suit (i.e., in air), since a limited amount of body heat storage can occur before performance degradation or risk of heat illness is encountered. For the average man weighing 70 kg, heat storage of 70 watt-hours will raise deep body temperature approximately 1^oC, from a normal 37.5^oC to 38.5^oC, about the limit for safe, effective operation. If one assumes that this storage is incurred over a 2-hour period, i.e., that the diver loses 35W less than he produces, the minimum H_s is given by the expression

$$H_s = 0.9M - 35$$

where M equals metabolic heat production in watts. This expression assumes that 10% of M is lost by respiration, and includes the evaporation from the lungs. Heat loss by sweating will normally not be a factor in body cooling in most dry suit/undergarment combinations since they are impermeable. The exception occurs when the undergarment is porous or of fiber construction (such as the Arctic Explorer or O'Neill Benthos II undergarments). In these cases, a small amount of heat can be transferred outward by an evaporation-condensation cycle strictly within the undergarment (1). For the present discussion, however, this minor and transient avenue of heat loss may be safely ignored. The other factors needed to specify a maximum air temperature are the diver's skin temperature and metabolic heat production. In an impermeable suit with $1^{\circ}C$ body temperature elevation, mean skin temperature will be about $36^{\circ}C$ and the skin will be sweat wetted. If the diver is engaged in only light activity, a metabolic heat production of 200W is a reasonable assumption; if M goes higher, the maximum air temperature will be reduced but, on the other hand, heat loss can be increased by opening zippers, etc. to increase ventilation.

A similar approach can be used to determine the minimum water temperature for which a suit will provide acceptable protection at the surface. The guidelines proposed for divers (3) recommend a maximum heat debt of 200 kcal (230 watt-hours) and a minimum mean skin temperature of $25^{\circ}C$. If a water exposure is to last two hours, H_s should therefore be equal to 0.9 M plus 115. Metabolic production for an active diver in water can be assumed, for demonstrating the prediction technique, as 400W. Higher activity will lower the predicted minimum water temperature and lower activity will raise it. Mean skin temperature will be assumed to average $29^{\circ}C$ during the two hour exposure.

This value is slightly higher than the average which would be measured while the skin cooled from a normal 33°C mean to the minimum recommended value of 25°C, but the error will be on the safe side, i.e., water temperature estimates will be high.

In predicting ambient temperature limits in air and water in this manner, it must be recognized that these insulation values were obtained on a stationary manikin, in still water, and should be modified for diver and/or water motion. His body motion will cause air movement within the suit, and a reduction in its insulating effectiveness. The extent of the reduction will depend on the fit and design characteristics of the suit and undergarment (when worn), and on the diver's activity level. For lack of a better estimate, the intrinsic insulations of the systems in Table III will be reduced by 10% to account for "pumping" effects; intrinsic insulation, i.e., that of the system itself exclusive of the contribution of the surface air or water film, is calculated by subtracting the value for the nude manikin from the total insulation value for a system, in air or water, respectively.

For the predictions, the insulating values in Table III will also be adjusted to reflect likely changes in the insulation values of the air and water films on the suit surfaces during actual diver exposures. During air exposures, air motion will generally be higher than in our studies (0.2 m/s); the diver's movements will also increase air flow over the suit surface. Both will lower the insulation of the surface air layer, and its contribution to a suit's total insulation value. Accordingly, the air film insulation will be assumed to be 0.4 clo, corresponding to a combined air/diver motion of 1.8 m/s (4 mph). In water, the contribution of the surface film will be greatly different for a diver than for the manikin. Theoretical considerations (2,4) indicate that this film contributes only about 0.05 clo in slowly moving water; of the 0.18 clo insulation measured for the nude manikin in water, the waterproof coating probably accounted for 0.13 clo. Increased water motion reduces the film insulation, but only by a few hundredths of a clo; changes with motion can be estimated from earlier copper manikin data shown in Figure 2. No adjustment is considered necessary to account for changes in film coefficient with motion, but the 0.13 clo attributable to the waterproof coating will be deducted from total insulation values, i.e., the film insulation itself will be taken as 0.05 clo.

To summarize these adjustments, insulating values in Table III will be modified for the predictions as follows:

For air exposures:

$$I = 0.9\,(\text{air clo} - 0.84) + 0.4$$

For water exposures:

$$I = 0.9\,(\text{water clo} - 0.18) + 0.05$$

Adjusted insulating values in air and water, and predictions of maximal air and minimal water temperatures for the various dry suit combinations under the assumptions that have been made, are given in Table VI. No values are given for an undergarment worn alone (systems 18 through 22 in Table III) since such usage would be unlikely in practice.

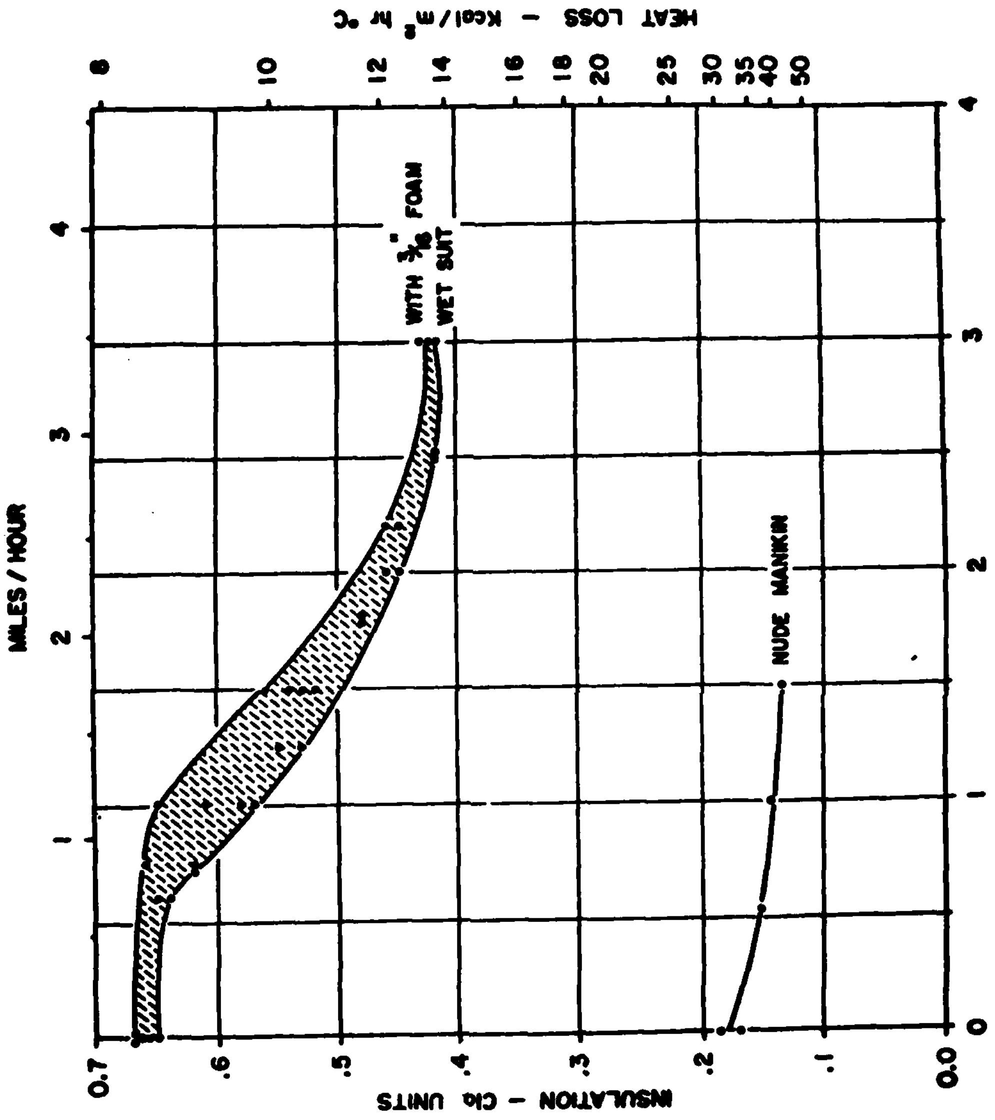

Figure 2. Effects of water motion on total insulation value

TABLE VI

ADJUSTED TOTAL INSULATION VALUES AND PREDICTED TEMPERATURE LIMITS FOR AIR AND WATER ENVIRONMENTS

SUIT OR ENSEMBLE	Air Exposure		Surface Immersion	
	Adj clo	Max Air Temp (°C)	Adj clo	Min Water Temp (°C)
Outer Garment Only:				
1. Unisuit	1.37	19	0.73	14
2. Viking	0.79	26	0.23	24
3. O'Neill Supersuit	1.14	22	0.69	14
4. White Stag	1.21	21	0.75[1]	13
5. Bayley Aquastatic	1.25	20	—	--
6. Imperial	1.32	19	0.74	13
7. Sub Aquatic Systems	1.02	23	0.61	16
Ensemble:				
8. Unisuit w/Arctic Explorer Undergarment	1.84	13	1.13	5
9. Viking w/Viking Undergarment	1.53	17	0.79	12
10. O'Neill Supersuit w/Benthos II Undergarment	1.74	14	1.09	6
11. White Stag w/Neoprene Shorty Undergarment	1.44	18	0.89[1]	10
12. Unisuit w/2 Sets Arctic Explorer Undergarments	1.88	13	1.28	2
13. Viking w/Benthos II Undergarment	1.37	19	0.65	15
14. Unisuit w/Viking Undergarment	2.05	10	1.13	5
15. O'Neill Supersuit w/Navy Waffle Undergarment	1.35	19	0.77	13
16. Unisuit w/Spacer Leggings	1.49	17	0.94	9
17. O'Neill Supersuit w/Spacer Leggings	1.45	18	0.90	10

1. Suit deflated

From the standpoint of protection in cold water, the Unisuit with either the Arctic Explorer Undergarment (one or two sets) or the Viking Undergarment is most effective, followed closely by the O'Neill Supersuit and Benthos II Undergarment (systems 12, 8, 14 and 10 in that order). All protect for two hours at water temperatures ranging from 2°C to 6°C. It should be recognized that these systems are also those with the lowest maximum air temperature limits (10°C to 14°C); this consequence is unavoidable since the controlling factor is the intrinsic insulation of the system. While increasing the insulation value lowers the water temperature which can be tolerated, it also lowers the maximum temperature acceptable for air exposure. The maximum air temperature limit for a system would of course be raised if its intrinsic insulation in air were lower than in water. The reverse is true in practice since water pressure on the dry suit system generally lowers intrinsic insulation during water immersion. This loss of intrinsic insulation has the effect of reducing the difference between the predicted maximum air temperature and minimum water temperature in Table VI. For example, systems 8 and 14 have the same insulation in water and, therefore, the same predicted minimum water temperatures. However, system 14 provides 0.21 clo more in air than system 8 (2.05 clo vs 1.84 clo) and its maximum air temperature is 3°C lower (10°C vs 13°C). On this basis (and the fact that its insulation loss in water is 0.21 clo greater), system 14 would be judged less desirable than system 8.

Since the air-water temperature differences in Table VI are influenced both by the loss of insulation in water as well as by the actual level of insulation, it is difficult to determine optimal requirements or the suitability of the various dry suit combinations using the predicted results. One alternative, which can provide important guidance, is to predict temperature limits over a range of thermal insulation values. These results may then be used to determine (1) level of insulation required for immersion at a given water temperature, (2) maximal air-water temperature difference which can be accommodated (assuming no suit insulation loss in water), or (3) the actual permissible air-water temperature difference if the amount of insulation loss in water is known or can be estimated. Such a compilation of predicted values is given in Table VII.

TABLE VII

PREDICTED TEMPERATURE LIMITS FOR AIR AND WATER EXPOSURES IN TERMS OF INTRINSIC INSULATION

Intrinsic Insulation (clo)	Total Insulation[1] In Air (clo)	Total Insulation[1] In Water (clo)	Max Air Temp (°C)	Min Water Temp (°C)
0.5	0.90	0.55	24.8	17.4
0.75	1.15	0.80	21.7	12.1
1.0	1.40	1.05	18.5	6.9
1.25	1.65	1.30	15.4	1.6
1.5	1.90	1.55	12.3	- 3.7[2]

1. Obtained by adding 0.40 and 0.05 clo, respectively, to intrinsic insulation value to account for surface-film insulation of air and water.

2. Obviously a water temperature of -3.7°C is impossible since sea water freezes at -2.5°C.

This Table shows that, to protect a diver almost to the freezing point (1.6°C), a dry suit combination with 1.25 clo intrinsic insulation (1.3 clo total in water) is required.

If this suit lost no insulation during immersion, its insulation in air would be 1.65 clo and it could be worn satisfactorily in a 15°C environment for a few hours. However, if the suit was less than ideal and lost 0.25 clo during immersion, its intrinsic insulation in air would have to be 1.5 clo (1.9 clo total); use in air warmer than 12°C would then be contraindicated. Thus, a loss of 0.25 clo in water would reduce the air-water temperature range for the suit by 3°C. It is interesting to note that this example actually represents the findings for system 12 in Table VI. If no insulation reduction had occurred in water, this system (Unisuit with 2 sets Arctic Explorer Undergarments) would have been adequate for protection well below freezing (-3.7°C) or acceptable for more than two hours exposure at a 400W activity level.

The results in Table VII show very clearly that some sort of adjustment will be required to make a dry suit that protects down to the freezing point of water acceptable for wear in air. Serious overheating can be expected above 15°C with the diver moderately active unless zippers are opened or gloves/hood removed to increase heat dissipation. The ease of making such adjustments, as well as the problems which might arise (e.g., snagging on open zippers) are obviously important considerations from a suit design standpoint.

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APPENDIX A

Dry Suits

Recently, several dry suits have appeared on the commercial market. All but one of these suits are made of 1/4-inch closed cell neoprene (CCN) foam. Seven dry suits and five types of undergarments were selected for evaluation. The suits selected were noticeably different in zipper arrangements and/or length. Insomuch as possible, all suits were configured with boots and hoods attached.

1. Parkway/Poseidon Unisuit - This one-piece suit, constructed of a 1/4-inch neoprene foam with nylon on both sides, features an attached hood and boots, and a 52-inch waterproof zipper running from the base of the back of the neck, down under the crotch, and up to the waist. The suit seals around the wrist and neck by the contact of smooth skin neoprene with the diver's skin. The seal at the wrist is made from a 3/16-inch nylon outside/smooth skin-inside neoprene cuff. The seal is made when the diver's wrist is placed through the cuff. The neck is sealed by a thin neoprene collar which is pulled down, around the neck, after the head has been inserted through the neck opening. The dry glove is separate. The attached boots are dipped in raw neoprene, providing a tough, durable sole.

2. Viking Variable Volume Dry Suit - This one-piece suit, constructed of a 1.1 mm-thick rubber coated polyester, tricot knit fabric, with boots attached, features a latex-rubber neck seal and cuff. Entry is through the neck opening. A separate latex collar is folded over a plastic neck ring and used to seal at the neck. Latex cuffs are attached to the sleeves and seal against the wrist as the hand is passed through. The hood, also made of latex, is a separate item. The seams are stitched, strapped with rubber, and vulcanized. The boots are full-cut and contain a rigid molded sole.

3. O'Neill Supersuit - This is a one-piece suit, constructed of 1/4-inch neoprene foam, with nylon on both sides. Seams are cemented and strapped on the inside with 1/16-inch neoprene with nylon on one side. Soft-soled boots are attached. Both the neck seal and wrist seals are made of nylon one-side neoprene which is folded under to place smooth neoprene against the diver's skin for the seal. A 33-inch waterproof zipper is located across the back of the shoulders. A separate hood, handwear, and overshoes are used.

4. White Stag Thermal-Air Dry Suit - This is a one-piece suit, constructed of 1/4-inch neoprene foam with nylon on both sides. Seams are cemented, stitched, and strapped inside with 1/16-inch neoprene foam with nylon on one side. The suit has a zipper running from the waist around the neck and back to the waist. Boots and hoods are attached, but can be obtained separately. Wrist and neck seals are 1/8-inch neoprene with skin on the outside and nylon on the inside.

5. Bayley Aquastatic Dry Suit - This suit is of one-piece design, with hood and boots attached, and constructed of 1/4 inch neoprene foam, with nylon on both sides. Seams are cemented, stitched, and strapped on the outside with knitted tape. Smooth-skin neoprene is on the inside of the cuff to seal at the wrist. The neck seal is made of two smooth-skin neoprene strips attached to the

neck of the suit. A 40-inch waterproof zipper is located across the back of the shoulders for entry. Wet gloves are separate.

6. Imperial Dry Suit - A one-piece configuration with hood and boots attached and constructed of 1/4-inch neoprene (Japanese make), with nylon on both sides. Seams are cemented and stitched on the outside. A 30-inch zipper is located across the back for entry. Both the wrist and neck seals are folded under with smooth skin neoprene sealing against the diver. Trigger finger type gloves are available separately. Boots are constructed with a firm felted-type sole.

7. Sub-Aquatic Systems - A one-piece suit constructed of 1/4-inch neoprene foam, with nylon on both sides. Sock-type boots are attached, with nylon on the outside. Seams are cemented and stitched on the outside only. Boots are strapped on the outside with 1/16-inch neoprene, and with nylon outside strapping. A 32-inch waterproof zipper is located across the back of the shoulders. The hood and handwear are separate. Wrist seals and neck seals are folded under.

Undergarments

1. Parkway/Poseidon Arctic Explorer Undergarment - A one-piece, deep pile polyamide undergarment with separate hood made of the same material.

2. Viking Undergarment - A lightweight, 3/16" open cell, urethane foam undergarment. The foam is fabric lined for comfort and has separate booties and hood.

3. O'Neill Benthos II Undergarment - This one-piece, fiberfilled coverall undergarment has booties attached. No hood is provided. The outside is rip stop nylon with water repellent characteristics.

4. White Stag "Shorty" Undergarment - This is a 1/8" nylon two side neoprene undergarment. The undergarment is sleeveless and short legged.

5. <u>NCSL Spacer Leggings</u> - This is a waist-high undergarment fabricated of three layers of fabric. The inner layer is 100 percent cotton for comfort and absorption. The outer layer is a nylon tricot for smoothness to aid in donning the dry suit. The middle layer is comprised of one or two layers of various styles of trilok spacer fabric. Strips of an expansion fabric are used throughout to increase mobility at the joints.

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