TITLE

IMMERSED CLO INSULATION IN MARINE WORK SUITS USING HUMAN AND THERMAL MANIKIN DATA

Immersed clo Insulation in Marine Work Suits Using Human and Thermal Manikin Data

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The immersed clo value of a series of 11 marine work suits has been measured using both humans and a thermal manikin. In still water, there is no significant difference in the measurements. Turbulent water significantly reduces the immersed clo value. The manikin errs on the safe side and consistently overestimates this decrement in insulation, and the reasons for this are discussed. Not intended to replace human physiological testing, the manikin is an excellent apparatus for the examination of conditions not easily or ethically possible to represent using humans. A good fitting suit with efficient neck, wrist and ankle closures which reduce flushing of water is essential to make an effective marine work suit.

NUMEROUS OCCUPATIONS, whether military or civilian, require that personnel work on or over cold water, thus creating the possibility of accidental immersion. Protective work clothing, or marine anti-exposure work suits must provide protection upon accidental entry into cold water such that they: a) lessen shock upon entering the cold water; b) delay the onset of hypothermia; and c) provide flotation.

Of the three requirements, flotation is the easiest problem to solve. With the addition of buoyant materials, which can also provide thermal protection, sufficient flotation can be achieved. However, the increased insulation and buoyancy must not compromise the comfort and workability of the suit, which must be worn continually and allow the wearer to perform all necessary tasks.

Although the environmental conditions to which the individual may be exposed upon accidental immersion can range from calm, cool water to turbulent, ice-cold water, the majority of investigators have studied cooling only under laboratory conditions, with little emphasis on the actual sea-state.

Steinman *et al.* (10) conducted a study in open water which compared the protective ability of anti-exposure suits in calm versus rough water. They found that increased water turbulence caused a reduction in the thermal protection afforded by the garment, an increase in the mean rectal cooling rate, and a decrease in back temperature. They attributed the differences to water flushing into the suits, which occurred while the subjects were attempting to maintain airway freeboard, and through body movements caused by the wave action itself. In agreement with this theory, Hayes *et al.* (6) have also reported a concurrent increase in energy expenditure during immersion in rough water.

Nunneley *et al.* (8) have identified features which will affect insulation of immersion garmentry. These include: material thickness and compressibility; water permeability of fabric; and integrity of seals. An additional feature to consider in turbulent water conditions is the fit of the garment—one that fits loosely allows more internal flushing if it leaks or is designed on the "wet suit" principle. Steinman *et al.* (10) reported increased cooling rates from 9% for a tight fitting garment (short wet suit) to 100% for the loosest fitting garment (boat crew coveralls). However, most anti-exposure work suits are essentially wet suits and are, therefore, expected to leak. Although the effects of leakage on the thermal insulation of a garment have been studied (3,11), further investigations under rough water conditions where flushing occurs are required.

One method of assessing the thermal protection pro-

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vided by anti-exposure work suits is to use a thermal manikin. In this way, the investigator avoids the methodological problems, ethical considerations, and physiological limitations associated with employing human subjects (4). Hall and Polte (3) used a copper manikin in air and in calm water, dressing in dry and wet clothing, to measure the effects of leakage and hydrostatic compression on clothing insulation. More recently, manikin data has also been combined with computer modelling of the thermoregulatory response in man to study the interactions between tissue and clothing insulation (8).

The purpose of the present study was two-fold. First, we wanted to compare the measured values of immersed clothing insulation as determined by human or by manikin tests. Second, we wanted to determine the influence of sea state, that is, rough versus calm water, on the thermal protection provided by marine anti-exposure work suits.

METHODS

Subjects

Five healthy male divers between the ages of 26 and 50 volunteered and gave their informed consent to participate in the study approved by the Human Ethics Committee of the Defence and Civil Institute of Environmental Medicine. All subjects were sea survival instructors and accustomed to prolonged cold water exposure. Skinfold thicknesses were measured with Harpenden callipers at seven sites: triceps, subscapular, biceps, suprailiac, abdominal, front thigh and calf. An estimation of percent body fat was calculated according to the formula of Durnin and Womersley (2). The physical characteristics are shown in Table I. Since total immersion time was less than 1 h, the water temperature was kept at approximately 20°C; and as all subjects had some clothing protection, with Ethics Committee approval, it was deemed unnecessary to monitor rectal temperature.

Physiological Monitoring

Each subject was fitted with four heat flow sensors with a composite thermistor units (Concept Engineering, Old Saybrook, CT). The units were placed on the left side of the body on the midcalf, forearm, midback and abdomen. Because we were limited to four heat flow discs, these sites were deliberately chosen for their likelihood of being the most susceptible to water ingress, therefore, possible flushing; and because they represented the two major body segments, torso and limbs. A Hewlett-Packard data acquisition system (HP 3455A Digital Voltmeter, HP 3495A Scanner and HP 85 Computer) was utilized to collect data and calculate heat flow (W/m^2) and surface skin temperature (°C). To facilitate comparisons between the manikin and the human, mean heat flow (MHF) and mean skin temperature (MST) were calculated for each subject using weighting factors which approximated the relative surface area of the appropriate body segment of the manikin. The factors were as follows:

$$\text{MHF or MST} = (0.5 \times \text{calf}) + (0.2 \times \text{arm}) + (0.15 \times \text{back}) + (0.15 \times \text{abdomen})$$

Clothing insulation values for the human immersions were calculated from MHF and the temperature gradient between MST and the water as follows:

$$\text{Insulation (clo)} = \left[\frac{\text{MST} - \text{T(water)}}{\text{MHF}}\right] \Big/ 0.115$$

Manikin Studies

A Thermal Instrumented Manikin (TIM) was designed and constructed to measure insulation of survival suits immersed in water (9). A computer based system controls and measures the temperature and power inputs of 13 thermally isolated, cast aluminum sections. The total surface area of the manikin is 1.736 m^2. The 13 sections and relative percentage of each section are shown in Table II. The relative percentage of surface area of torso to limbs was 50:50. The mobility of the manikin is limited to single-axis rotation in the shoulder and hip joints. The manikin was fitted with the clothing ensemble, attached to a buoyant frame and lowered into the water. To determine the clothing insulation of the manikin, a constant surface temperature, generally 3°C above that of the water, is maintained for each section by the heater embedded within it. The total power (in Watts) required to maintain the set point temperature is divided by the manikin surface area to give a MHF. The same calculation is then carried out, as for the human testing to determine insulation. The insulation of the clothing was calculated from the temperature gradient between the manikin surface, the water, and the mean heat flow (9). Fig. 1 shows the manikin in its test position. Each of the eleven suits was tested twice, once in still water, the second in water stirred with a wave generator.

TABLE I. ANTHROPOMETRIC CHARACTERISTICS OF THE FIVE SUBJECTS.

Subject	Age (years)	Height (cm)	Weight (kg)	B.S.A. (m^2)	Mean Skinfold Thickness* (mm)	% Body Fat (%)
A	26	193.0	84.1	2.16	5.9	16.4
B	34	182.9	79.1	2.00	5.9	19.0
C	36	182.2	86.4	2.07	13.2	29.0
D	50	180.3	93.2	2.15	19.4	31.6
E	35	182.9	113.6	2.34	8.8	23.9
Mean	36.2	184.3	91.3	2.14	10.1	24.0
S.D.	8.7	5.0	13.5	0.13	3.0	6.4

* Mean of seven sites: triceps, subscapular, biceps, suprailiac, abdominal, front thigh, medial calf.

TABLE II. RELATIVE PERCENTAGE AND SURFACE AREAS (m^2) OF THE 13 SECTIONS OF THE MANIKIN.

Manikin	Area (m^2)	Percentage (%) of Total
Head	0.136	7.8
Chest	0.156	9.0
Back	0.166	9.4
Left Arm	0.102	5.9
Right Arm	0.114	6.6
Left Hand	0.048	2.8
Right Hand	0.049	2.8
Abdomen	0.055	3.2
Buttocks	0.086	5.0
Left Leg	0.332	19.1
Right Leg	0.356	20.5
Left Foot	0.067	3.9
Right Foot	0.069	4.0
Total	1.736	

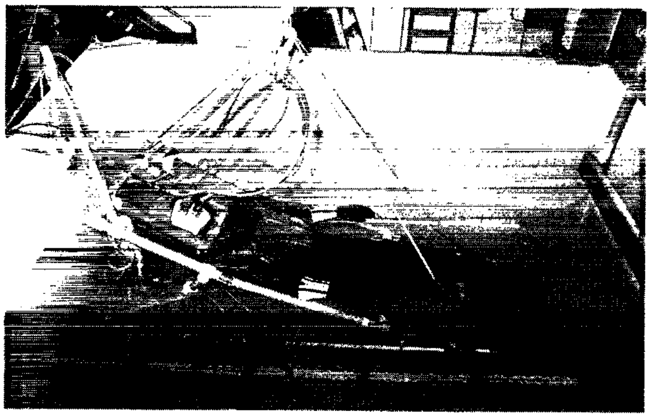

Fig. 1. The thermal manikin suspended in position prior to immersion in still water.

Marine Anti-Exposure Work Suits

The suits ranged from two-piece polyvinylchloride-coated nylon fishing attire to fully insulated one-piece immersion suits with deliberately added and designed buoyancy. All of the insulated suit pieces consisted of close cell foam. Five of the suits were equipped with insulated hoods, two of which provided inflatable headrest pillows for neck support and comfort. All of the remaining suits had uninsulated hoods. Of the 11 suits, 8 had storm flaps secured with velcro to cover the front zippers. To minimize water entry and water movement within the suit, most of the suits provided a number of straps. The straps were of the cinch, velcro, or elastic varieties and were located at the wrist, upper arm, thigh, and ankle, depending on the number provided by the suit. Six of the suits also provided waist belts. A more detailed description is provided in Appendix A.

The objective was to select as many current marine and prototype work suits as possible and measure their insulation using the manikin, then to compare these values to values measured using humans. Each subject wore a minimum of two different suits and, where possible, a third suit.

For ease of application of the results to the later development of standards, the suits were divided into three categories based on the insulation values obtained during preliminary manikin tests. The high insulation group (H) consisted of three suits with immersed clo values greater than 0.35 (No. 1, 2, 5, and 8), a medium group (M) consisting of four suits with clo values ranging between 0.2 and 0.35 (No. 3, 4, and 6), and a low group (L) of four suits with clo values less than 0.2 (No. 7, 9, 10, and 11) (see Appendix A).

Human Testing—Immersion in Still vs. Turbulent Water

Following the attachment of all the physiological leads, the subjects donned undergarments followed by a preselected anti-exposure work suit. To be consistent, undergarments consisted of 100% cotton pants (denim material), wool or pile socks, and a 100% cotton work-shirt. Hands and feet were protected by simple knee-high fishermen's style rubber boots and work gloves. A physician with full resuscitation equipment was present throughout the whole experiment.

All subjects entered the still water (temperature range 19.3 to 20.4°C) with the water kept stirred by means of bubbling compressed air through the tank. All suits were worn in the closed state, that is, with all closures secure and straps fastened, and assumed a natural floating position. This was done to represent as closely as possible the floating position of the manikin during the manikin testing. However, in order to ride the waves and maintain a clear airway for a regular breathing cycle, the subjects crossed their arms and held their heads clear of the water to breathe. Since some of the low insulation suit ensembles had little buoyancy for the subject to maintain airway freeboard over the full period of immersion, rubber surgical tubing was attached to the side of the tank, and looped through the subjects' elbows and ankles to position, support and stabilize them. It standardized their location in the tank to mimic that of the manikin, it avoided any injury by contact with the side walls and prevented the requirement of treading water when wearing the lighter buoyant suits (Fig. 2). The still water immersed clo value was determined from MHF and the temperature gradient between MST and the water once the MHF and MST had plateaued and there was less than a 0.05 clo change in insulation over a 5-min period. This point was usually reached 25 to 30 min into the immersion. A 5-min average for MHF and MST was used for the calculations.

At this point, because we were simply using the human as a heat source, it was possible for convenience to continue with turbulent water testing immediately following the still water testing. Thus, the wave generator was activated to simulate turbulent water conditions. Waves with a period of 2.1–2.7 s and an amplitude of 25–40 cm were produced. Body position was such that the waves did not cover the head of the subjects. Both MHF and MST plateaued during the turbulent condition within 15–20 min and the new immersed clo values were then similarly determined at this point.

The group means for immersed clo values were calculated following which immersed clo data for each suit were then compared by paired t-statistics with data obtained from manikin studies that had been conducted on the same suits.

TABLE III. COMPARISON OF INSULATION VALUES BY GROUPS IN 20°C STILL AND TURBULENT WATER—HUMAN AND MANIKIN (*$p < 0.001$).

Sea State	Suit	Human (clo)	Manikin (clo)	Difference (human vs. manikin) (%)
Still	Heavy	0.39 ± .04	0.39 ± .15	0
	Moderate	0.24 ± .03	0.24 ± .07	0
	Light	0.18 ± .04	0.16 ± .05	11.1
Turbulent	Heavy	0.27 ± .10	0.17 ± .09	37
	Moderate	0.18 ± .03	0.11 ± .04	38.8
	Light	0.12 ± .04	0.07 ± .03	41.7

TABLE IV. COMPARISON OF PERCENTAGE DECREASE IN SUIT INSULATION STILL TO TURBULENT WATER CONDITIONS.

Suit	Difference (Still vs. Turbulent)	
	Human (clo)	Manikin (clo)
Heavy	30.80%	56.40%
Moderate	25.00%	54.20%
Light	33.30%	56.30%
Mean	29.70%	56.70%

creases in heat flow at the arm and abdomen sites. The rigidity of the manikin along with its floating position did not change during the turbulent testing. This resulted in the arms and abdomen areas entering the water with each wave motion and acted rather like a scoop. The humans naturally crossed their arms across their chest thus avoiding the scooping action of the cuffs against the oncoming waves; this acted as a barrier to water entry. Furthermore, the humans rode each wave to keep the airway clear for each respiratory cycle, whereas the face of the manikin was awash more of the time.

Mild shivering was noted in thinner subjects and those who wore suits with low insulation. We were not able to measure how much this contributed to increasing flushing within the suit, but it would certainly be a factor in increasing the cooling rate in a longer term survival situation.

Human vs. Manikin Comparison

The use of manikin provides distinct advantages for the comparative testing of a very large range of immersion suits prior to more detailed physiological testing using human subjects. Apart from the important ethical advantages, the manikin offers consistency, an advantage humans cannot offer due to variations in their anthropometry and physiology. However, to interpret manikin test results accurately, the relationship between human and manikin testing results must be understood.

While there were no significant differences between human and manikin tests of the suit in still water, differences did occur in turbulent water. It is our opinion, however, that these results do not invalidate the use of manikin testing of these anti-exposure work suits or any other survival suits, even during turbulent water trials. First, the decrement in insulation was always greater with the manikin as compared to the human, thus these differences might possibly be compensated for, if necessary. Second, if a particular standard for immersed clo values is being aimed for, one errs to the benefit of the human, since a greater effective insulation will result.

The rubber tubing was introduced for three reasons. First, to provide some stability to the subjects in the waves; second, to present the requirement to tread water when wearing the lightly buoyant suits; and, lastly, to mimic a similar angle to that adopted by the manikin.

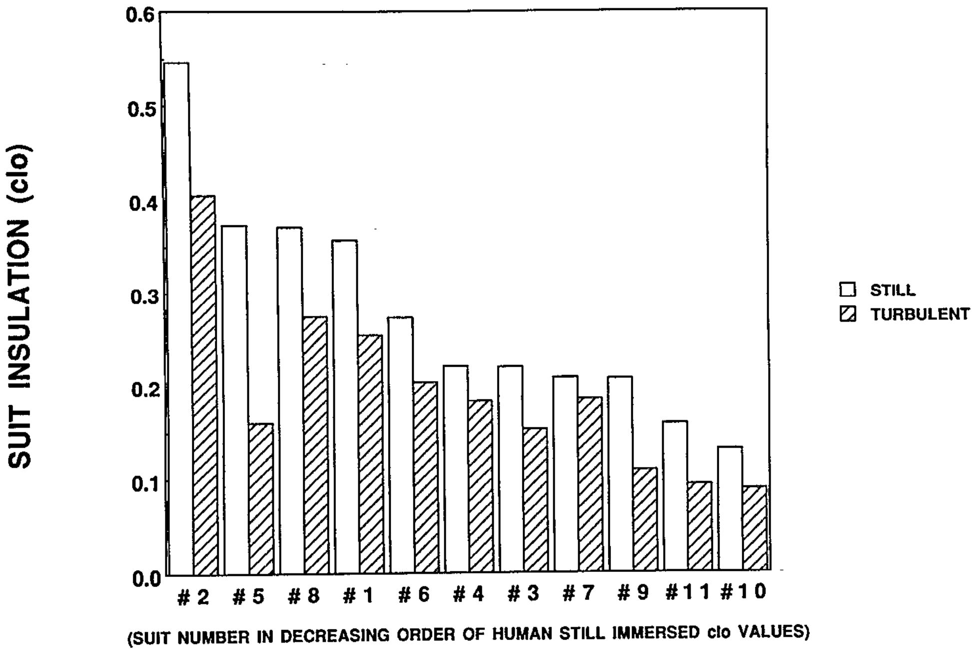

Fig. 7. A comparison of the thermal insulation of work suits measured using human subjects in still and turbulent 20°C water.

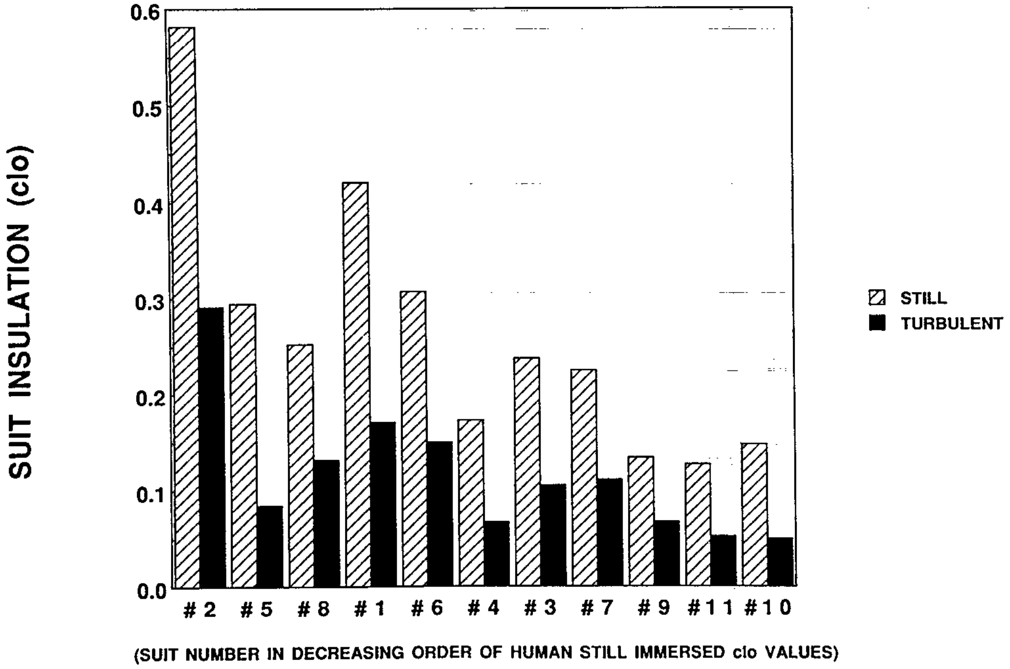

Fig. 8. A comparison of the thermal insulation of work suits using the manikin in still and turbulent 20°C water.

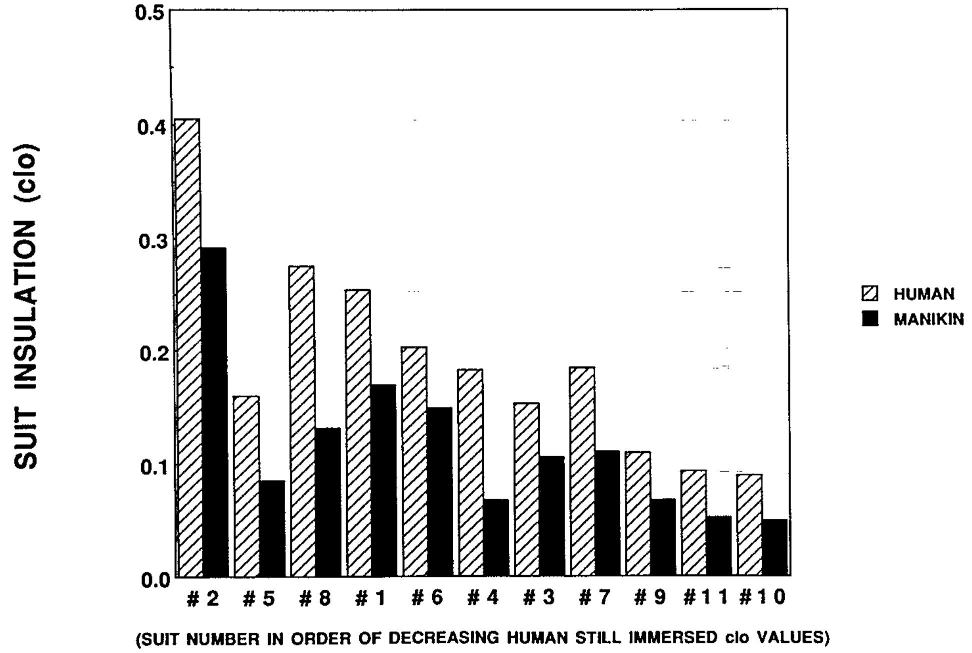

Fig. 9. A comparison of thermal insulation of work suits measured using human subjects and the manikin in turbulent 20°C water.

We do not think that this had any effects on our findings.

It is important to note physical differences between testing with humans compared to manikins. The manikin is a rigid structure which maintains a fixed floating position in the water. This increases the likelihood of water ingress at neck seals and water flushing over the face and head, since respiration is not a consideration; it is thus a much more severe test for any protective suit. In contrast, a human must maintain airway freeboard and does so by naturally adopting a tighter foetal body position that raises the head above the water. In addition, this position reduces the amount of flushing, and in turn, convective heat loss. The rigidity of the manikin restricts its flotation position, whereas the position of the human subjects in this experiment varied depending on the amount and location of buoyancy within the suit. With a more buoyant suit, the subject lies almost horizontal, while with other, less buoyant suits, the floating angle approached as much as 30°. As Light *et al.* (7) documented, the flotation angle of the individual is vital not only in terms of wave riding and the maintenance of airway freeboard, but also in terms of heat transfer.

The second physical difference between a human and a manikin is the absence of vascularization in the latter. A vascular system allows for vasoconstriction in cold conditions as a mode of reducing heat flow from the extremities and increasing tissue insulation. The manikin works on the principle of maintaining a constant surface temperature whereas a human will allow the skin temperature to fall.

Finally, the compressibility of human tissue makes it easier to secure straps and closures on a human torso and limbs than on those of a rigid, hard surfaced manikin. This amounts to a better overall fit on the human subjects and a reduction in the amount of leakage, leading to higher immersed clo values during the human tests as compared to the manikin, especially in turbulent waters.

The Design of Marine Anti-Exposure Work Suits

In summary, immersion in turbulent water has been shown to decrease the immersed clo values of a suit as compared to still water. The magnitude of the decrease is dependent on a number of factors inherent in the suit design, such as the fit of the suit, and the number and location of effective closures provided. Even though there are obvious differences between human and manikin testing, immersed clo values are similar during still water trials; however, during turbulent water trials, the manikin values err on the side of safety and consistently over-estimate heat loss. With further research, it may be possible to produce appropriate correction factors to obtain reasonable correlations during the turbulent water testing. Finally, this study has shown that the thermal manikin is an excellent device for research and testing in still water, and with more research will be applicable for the more practical aspects of turbulent water.

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APPENDIX A: MARINE ANTI-EXPOSURE WORK SUIT SYSTEMS DESCRIPTIONS.

Suit #1: One piece, close cell foam insulated coverall with a storm flap covering the front zipper, a waist belt and gusseted lower leg zippers. The suit has velcro closures on the wrist and ankles and a cinch strap on each thigh. The hood is insulated and there is an inflatable pillow to support the head.

Suit #2: One piece, close cell foam insulated coverall with a storm flap covering the front zipper, a waist belt and gusseted lower leg zippers. The suit has cinch type closures at the wrists, thighs and ankles, each secured with velcro. The hood is insulated and there is an inflatable pillow to support the head.

Suit #3: One piece, close cell foam insulated coverall with gusseted front and lower leg zippers and a storm flap covering the front zipper. There are velcro closures on the wrists and thighs and an insulated hood.

Suit #4: One piece, uninsulated coverall with a close cell foam vest insert for buoyancy. There is a gusseted front zipper with a storm flap. There are stretch vinyl-like inner wrist seals and velcro closures on the outer wrist sleeves. There is an inner and outer velcro closure on each ankle and an uninsulated hood.

Suit #5: One piece, close cell foam insulated coverall with a front zipper with a storm flap and lower leg zippers. There are velcro closures at the wrists, thighs and ankles. The hood is uninsulated.

Suit #6: One piece, close cell foam insulated coverall with a gusseted front zipper with a storm flap and lower leg zippers. There are velcro closures at the wrists and cinch type thigh closures secured with velcro. The hood is insulated.

Suit #7: One piece, close cell foam insulated coverall with fully gusseted front and lower leg zippers. The front zipper has a storm flap. There is an inner elastic cuff at the wrist, ankles, and waist with velcro closures on the outer wrist and ankle sleeves. There are cinch type closures on the thighs and upper arms secured with velcro. The hood is uninsulated.

Suit #8: Two piece suit. The pants are an uninsulated, bib type, with horizontal rib snuggers and gusseted front and lower leg zippers. The front zipper has a storm flap. The thighs and ankles have cinch type closures secured with velcro and there is a belt around the wrist. The jacket is close cell foam insulated and has a neoprene beaver tail. There are cinch type closures on the wrists secured by velcro. The hood is detachable and insulated.

Suit #9: Two piece suit. The pants are an uninsulated, bib type with an outer and inner velcro closure on the ankles. The jacket has a close cell foam flotation vest insert with leg straps which can be secured to hold down the jacket. There is a belt around the waist and stretch vinyl-like inner seals with velcro closures on the outer wrist sleeves. The hood is uninsulated.

Suit #10: Two piece suit. The pants are an uninsulated, bib type with an elastic inner cuff adjusted with a velcro tab on the ankles. The jacket is uninsulated and has a belted waist and elastic inner cuffs with adjustable velcro tabs on the wrists. The hood is uninsulated.

Suit #11: Two piece suit. The suit consists of cotton backed PVC coated commercial rain attire with bib-type overalls and a jacket secured with three snaps on the front. The hood is uninsulated. The suit is also known as "traditional fishing attire".

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