SURVEY OF THERMAL PROTECTION STRATEGIES

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Introduction

The level of consideration given to diver thermal protection planning increases as water temperature drops below 25ºC (77ºF) and the duration of the dive increases. Additional planning is needed when the dive profile does not allow the diver immediate access to the surface, such as a significant decompression obligation. For example, a dive made to a depth of 90m (300 ft) with a bottom time of 30 minutes incurs over 4 hours of in-water decompression (*Table 14-3, the US Navy's Surface-Supplied Helium Oxygen Decompression Table*). This in-water decompression obligation can be shortened to 2 hours using surface decompression. However, in both of these scenarios the thermal stress loading takes place primarily during the in-water decompression portion of the dive when the diver is the least active and metabolic heat production is lowest.

In addition to surface decompression, there are other strategies for lowering or eliminating in-water decompression and subsequent thermal exposure. The only way to eliminate in-water decompression is by using a Class-I closed bell operated in either bell-bounce or saturation mode or a diver lockout submersible. The use of a closed bell or submersible allows the diver to return to a dry environment after completing the work portion of the dive, minimizing the thermal exposure. The use of a bell or submersible also allows for longer work periods on the bottom while minimizing the total thermal stress loading. However, Class-I bell or submersible diving operations require larger support vessels to facilitate the bell/submersible handling equipment.

For this paper the assumption is made that the proposed diving will be done with surface supplied equipment and utilizes a Class II open bell. The open bell functions as a diving stage and way station but does nothing to minimize the dive's thermal exposure. The Class II bell is commonly used in commercial diving at depths greater than 67 m (220 ft) or on dives with greater than two hours of in-water decompression (ADCI, 2004).

Planning Thermal Protection Needs

The first step in selecting the thermal protection strategy is to define the level of performance decrement that is acceptable at the end of the work portion of the dive and/or at the end of in-water decompression. Work done by Weinberger and Thalmann (1990) at the Naval Medical Research Institute (NMRI) broke diver performance into three functional categories based on the individual's thermal state: fully functional, adequately functional, and barely functional. Table 1 provides the basic physiological parameters of these three categories.

Table 1.

Function Category	Core Temp 37 °C (98.6 °F)	Mean Skin Temp.
Fully	> 36.5 °C (97.7 °F)	> 29 °C (84.2 °F)
Adequately	> 36.0 °C (96.8 °F)	> 25 °C (*77 °F)
Barely	> 35.5 °C (95.5 °F)	> 20 °C (68 °F)

They went on to define the level of performance decrement that can be anticipated with each category.

- Fully Functional: **> 36.5 °C (97.7°F).** Little or no performance decrement due to thermal stress. Performance equal to 30 min dive conducted in warm water > 25 °C (77 °F).
- Adequately Functional: **> 36.0 °C (96.8°F).** Loss of mental performance and manual dexterity due to thermal stress, and may experience difficulty accomplishing mission tasks.
- Barely Functional: **> 35.5 °C (95.5°F).** Borderline for carrying out basic functions needed to maintain dive safety. This is the outside limit for exposure and is not intended for use in mission planning

When developing a dive plan, the planner should try to maintain the diver in the fully functional category. This is particularly important in the case of an untethered, free-swimming diver. The untethered diver needs to be fully functional to safely perform the dive and subsequent decompression. If the diver experiences the onset of hypothermia, and moves into the adequately functional category, the first skills to be impacted are the upper-level mental skills, such as the ability to do math and navigation. However, in the case of a surface-tended diver, decisions can be made at the surface and actions communicated to the diver and it may be acceptable to allow the diver to slip into the adequately functional category.

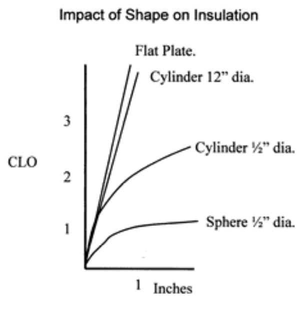


Figure 1.

In addition to the general thermal state of the diver, the hands and feet require special consideration as the water temperature drops below 7.2ºC (45ºF). This special consideration for the hands and feet is necessary because of the hemispherical geometry present on the tips of the fingers and toes, which limits the effectiveness of insulation (Nuckols, 1978; Beckman, 1996; van Dilla, 1957; Fig. 1). This in combination with reduced blood profusion to the extremities as the body experiences vasoconstriction in a response to cold. Without proper protection of the hands, finger temperatures will quickly drop to near ambient water temperature. In water temperatures below 12°C (53.6°F), the realm for Nonfreezing Cold Injuries (NFCI) is entered (Keating, 2000). NFCI is rarely mentioned or discussed in diving yet most individuals would recognize it by its more common name, “Trench Foot,” commonly seen in cold-weather military operations. Thalmann (1987) reported divers experiencing NFCI involving the hands and feet following dives in water colder than 7.2ºC (45ºF). One case of NFCI involving the face was reported by Dr. P. Hamner who was conducting diving operations in the Antarctic Ocean (Stinton, 1978).

The following guidelines for hand/foot exposure limits were recommended in *Cold Water Exposure Guidelines for Passive Thermal Garments* (Thalmann, 1990) and augmented with information from Keatinge (2000) to ensure that divers do not develop Nonfreezing Cold Injuries (NFCI).

Hand and Foot Temperature Limits

- Fully Functional 18°C (64.4°F)
- Non Freezing Cold Injury Threshold < Week
- 12ºC (54ºF) approximately 3 hours (Keatinge, 2000)
- 8°C (46.4°F) for maximum of 30 min
- 6°C (42.8°F) immediate rewarming

The gray area for hands, feet and face protection is in the 12°C (53.6 °F) to 8°C (46.4°F) range is

- Individual Differences
  - Personal physiology
  - Previous thermal injuries
  - Acclimatization?
  - Equipment
- Nonfreezing Cold Injuries (NFCI).

Diver Thermal Protection Strategies

The two primary strategies used in minimizing thermal stress in diving fall into two categories: passive and active. Passive thermal protection reduces the rate of heat loss by surrounding the diver in a layer of insulation. The wetsuits and drysuits represent the two most common passive approaches in use. The active approach utilizes an external energy source to maintain the diver in thermal equilibrium or offset losses. The free-flooding hot water suit represents the most widely used active approach. Other active systems utilizing electric resistance heating (Neste, 2001) or liquid-heat transport garments (tube suits) are used in combination with passive garments (Crepeau, 1993; Nuckols, 2001). However, these latter systems are not typically commercially available.

Diver Passive Thermal Protection

The passive approach is broken into two sub groups: the wetsuits and drysuits. Both of these approaches derive their insulation primarily from trapping and stabilizing gas.

Wetsuit

The wetsuit is typically made with closed-cell foam neoprene rubber and derives its insulation from gas trapped within the cell structure of the foam. The concept of the wetsuits was put forward and developed by Dr. Hugh Bradner of Scripps Institution in 1951 (Hanauer, 2003). Dr. Bradner noted in his initial work that the closed cells in the rubber would compress with increased depth and would lose insulation. However, this was not seen initially as a major drawback, because the UDT swimmer would be operating at depths less than 10 m (30 ft) and swimming at 0.5 knots.

Beckman conducted a series of tests at NMRI to better understand the impact of depth on the effectiveness of the wetsuit (1964)

Table 2. Depth insulation units (clo)

Insulation With Depth	
Surface	.59 clo
33 ft (10m)	.34 clo
66 ft (20m)	.27 clo
99 ft (30m)	.22 clo
132 ft (40m)	.18 clo
165 ft (50m)	.15 clo

The clo units utilized in Table 2 are units of insulation similar to the more common R-value and are equal to $0.18/m^2 \cdot hr$ or transfers of 5.56 kcal/°C·hr. Knowing the clo value of a garment gives the dive planner the means to estimate its effectiveness.

An additional factor not well understood about wetsuits is that the cell structure breaks down with repeated use. With the breakdown of the cell membranes, the cells flood and insulation value of the foam decreases. This breakdown was reported by Monji (1989) after studying the impact that compression and decompression cycles had on wetsuit insulation; however, his work did not address the mechanical impact wetsuits experience, which also breaks cell membranes down. This can be measured by simply weighing the suit after each dive. As the cells break down the suit holds more water and weight increases. The anecdotal comment here is that the diver always is impressed by the performance of their new wetsuit, not because the new wetsuit is that much better than the old suit when it was new, but that old wetsuit's performance deteriorated over time without the diver noticing it.

Even with these limitations the wetsuit continues to see wide use in shallow depths where it can provide durable and effective thermal protection for short-duration dives. However, the dive planner needs to understand its limitations when planning deeper and longer duration dives.

Drysuit

A drysuit, regardless of style, traps an envelope of gas (air being the most common gas) around the diver's body. Drysuits generally cover the diver's body, with the exception of the hands and feet, isolating the diver from the water. With additional suit accessories it is possible to totally isolate the diver from the environment. There are two primary construction styles used in fabricating drysuits. The first method utilizes the same closed-cell neoprene foam used in the construction of wetsuits and the second, shell drysuits are constructed using a wide variety of waterproof coated fabrics. The latter is becoming the more common style of drysuits. In both of these cases the suits are equipped with means for adding and venting gas during ascent and descent. Drysuits with valves are occasionally referred to as constant-volume suits or variable-volume suits, a hold over from when most of the drysuits used in the 50's did not have inlet and exhaust valve.

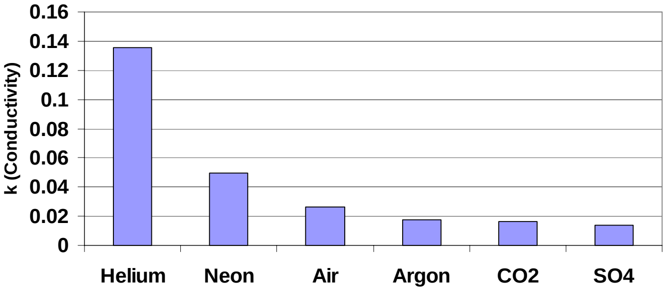
The total insulation in the foam-style drysuit is derived from the combination of the foam's insulation and the garments worn under the suit. The proportion of insulation from each layer is highly variable. Foam-constructed drysuits currently are offered in thicknesses ranging from 2-7 mm. The amount of insulation worn under the foam drysuit can range from a swim suit to the same insulated undergarment available for use with shell drysuits. In the foam-style drysuit, the insulation fraction provided by the foam decreases with depth just as it does with the wetsuit and the foam experiences the same damage with use as the wetsuit.

In the shell-type drysuit the total insulation primarily comes from the undergarments worn in conjunction with the suit. This allows divers using a shell-type drysuit to adjust the amount of insulation used to meet the anticipated exposure needs. Also, when alternate suit-inflation gases are used to increase the insulation value of the undergarments, the full benefit is available.

Drysuit Inflation Gas

Air has been the traditional drysuit inflation gas with some exceptions. In the past, when electric heating garments were used in combination with drysuits like the venerable Mark V or later during the 70's in saturation diving, the drysuits were inflated with heliox. The reason for use of heliox in saturation diving was that operators (COMEX in particular) did not want to introduce contaminants into the atmosphere of the saturation-chamber complex. The presence of helium has major impact on the performance of the suit because of its high conductivity (Table 3). Wattenberger (1978), in a series of thermal manikin tests done at ARIEN Natick facility, demonstrated that heliox in a shell drysuits would reduce the effective insulation of the suit ensemble by 71%.

Table 3. Gas conductivity.



The use of Argon as a suit-inflation gas has become very common in the technical diving community. Argon is used because its conductivity is less than that of air.

However, its value has been debated following tests done by Risberg and Hope (2001). The following bullet points outline how Risberg conducted the test:

- 26 Norwegian Navy Clearance Divers: age 21-33, mean wt 80.8 kg (2 dives each with 24 hr between dives) making a total of 52 dives
- Water temperature -1 ºC to 4 ºC (mean 2 ºC)
- Scuba with AGA full face mask
- 6.5 mm drysuit and woolly-bear undergarment
- Dives ~ 9 m for 60 min
- Divers did not know if they were using air or Argon
- Suit prepurged 3 times with Argon to ensure a high concentration in suit

During the dives the skin and core temperatures were monitored and the resulting data did not show any difference between air and Argon.

However, in a test done by Weinberger (1989) using CO_2 as the suit inflation gas, he reported a 52% improvement in suit insulation. Argon and CO_2 have conductivities that are comparatively close to air (Table 3). Why the great difference in test results? The different results can possibly be explained by the differences in the style of drysuits used. Risberg's tests utilized 6-mm foam drysuits and, as a result, a large fraction of the total insulation came from the foam. The addition of Argon would not change the intrinsic insulation of the foam and at 9m (29ft) of depth the foam contributes to a major portion of the total suit insulation. While in Weinberger's tests shell drysuits were used and the majority of the insulation came from the undergarments and, as a result, the CO_2 had a major influence on the outcome.

Hands

Optimum protection of the hands can be achieved with the use of dry gloves attached to the drysuit without wrist seal. The elimination of the wrist seal allows the free exchange of gas between the suits and glove (Fig. 2). The presence of a wrist seal can impede circulation of blood to the hand, which is already minimal when the hands are vasoconstricted. Work done by Thalmann (1987) and Stinton (1989) demonstrated that glove systems without wrist seals provided a higher level of protection for the hands. Thalmann reported that divers were able to rewarm the fingers by holding their hands over their heads and allowing the gas to inflate the glove/mitten to its fullest extent. In some cases with mitts the divers were able to draw their fingertips out of the mitt portion and rewarm them on their palms.

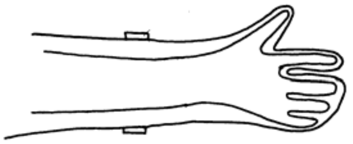


Figure 2.

Planning Thermal Exposure

Exposure planning has always been challenging for several reasons. The insulation values of passive garments are not well known and the tools to use them have not been widely distributed. Thalmann in *Cold Water Guidelines for Passive Thermal Garments (*1990) presented a simple algorithm to generate an exposure table. The algorithm can be set up on a Microsoft Excel spreadsheet and takes into account the following parameters: desired end of exposure functionality, water temperature, size of the diver, and the activity level. Table 4 was generated showing the levels of insulation needed to maintain a 75 kg (165 lb) diver fully functional in different water temperatures doing mild work. To use the table enter along the water temperature column then move across horizontally to the time in minutes that best meets the intended dive duration. From the time cell move up vertically to the clo value at the top of the column. The planner then can use a listing of clo values such as for different insulation packages and then determine a layering system most suitable for the planned dive. The challenge to the planner as the water temperature drops below 7ºC (45ºF) is protection for the hands and toes.

Table 4. Insulation requirements for a 75 kg diver.

Water Temperature		Insulation in Clo									
°F	**°C**	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
77	25	92	165	▨	▨	▨	▨	▨	▨	▨	▨
68	20	20	67	352	▨	▨	▨	▨	▨	▨	▨
59	15	**NR***	29	61	145	720	▨	▨	▨	▨	▨
50	10	**NR***	18	34	59	108	239	720	▨	▨	▨
46	8	**NR***	**NR***	29	48	80	146	352	▨	▨	▨
Below this line exposure limit may be controlled by fingers and toes											
43	6	**NR***	**NR***	25	40	64	105	194	352	▨	▨
39	4	**NR***	**NR***	22	34	53	82	134	720	▨	▨
36	2	**NR***	**NR***	20	30	45	67	103	137	560	▨
32	0	**NR***	**NR***	**NR***	27	39	57	83	216	493	▨
28	-2	**NR***	**NR***	**NR***	24	35	49	70	156	274	▨

NR*	Not Recommended inadequate protection
▨	Level of protection may be too high

In addition to the work done by Thalmann on exposure planning, Bradner (1985) compiled an exposure guideline (Table 5) for dive planning for COMNAVSPECWARGRU ONE. Bradner's guidelines included means for planning long duration dives using both wetsuits and drysuits.

Table 5. Exposure guidelines.

Dry Suit Under Garment Type	Clo (Air)
Polypropylene Underwear Medium wt.	0.1
Single Layer Fleece (200 gm/m^2)	0.3
Thinsulate 200 gm/m^2 Type B	0.6

Thinsulate 400 gm/m^2 Type B	1.3

Diver Active Thermal Protection

Free-Flooding Hot Water Suit

The free-flooding hot water suit (Fig. 3) works by surrounding the diver in a thermally neutral envelope of water 92-94 ºF (33-34 ºC). This envelope of water is maintained by means of continuous flow of water from the surface. Sea water or fresh water is supplied to a heater and/or heat exchanger at a rate between 2-8 gpm (7.5-30 lpm), is heated and then pumped down to the diver via an umbilical. The hot water suit is made with 5-6 mm closed-cell neoprene foam, the same as used in a wetsuit. The suit is equipped with a manifold and water distribution tubing for distributing and maintaining a layer of water around the diver's body. The manifold is also equipped with a bypass that allows the water to be diverted from the suits when the diver is entering or exiting the water or in the event water temperature control is lost. The suit is designed to fit very loosely to ensure water circulation around the diver's body. Water is continuously being discharged from the suits by way of the front zipper and junctions between the boots and gloves and around the neck.

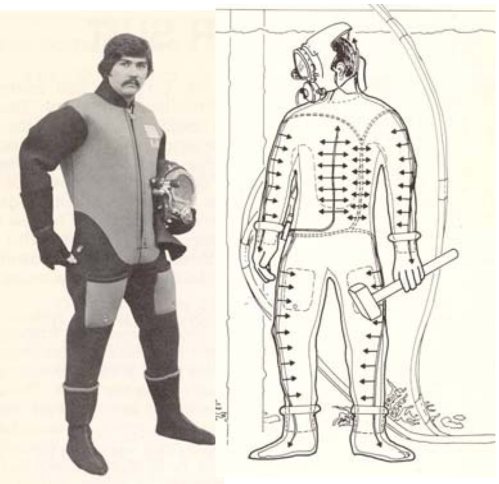


Figure 3a.

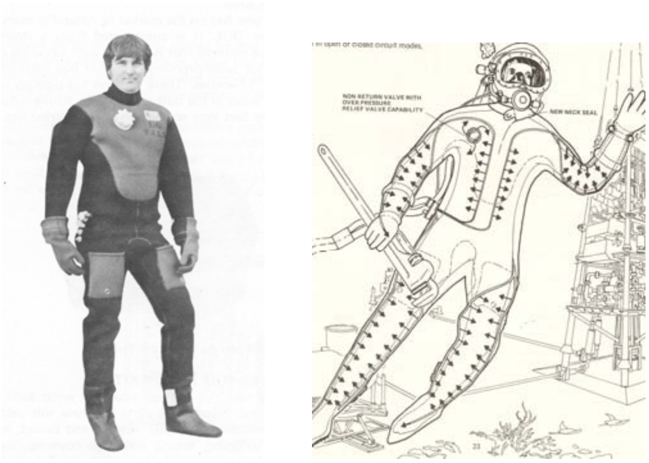


Figure 3b.

Other variants of the hot water suit have been built but their use has not seen wide acceptance in the commercial offshore industry, the primary user. The basic configuration was adopted and a proven track record of performance and durability were established, obviating the need for change. Currently there are four manufacturers of hot water suits worldwide and all the models are conceptually the same.

Specialized models of hot water suits have been built such as the NRV (Fig. 3), which is a closed design for use in special applications including diving in hazardous environments (Stinton, 2003). In addition to the NRV variant, closer fitting suits made with lighter materials have been built and used in applications requiring greater swimmability.

Table 6. Advantages and disadvantages of hot water suits.

Pros	Cons

• Long history of operational experience
• Robust
• Simple diver training
• Operate over wide temperature range without changes to the diver's equipment configuration
• Hands and feet are not impacted by lower temperature water
• Can be used in environments where the diver needs to be cooled
	• Topside support
	• Larger diameter umbilical for hot water supply
	• System Maintenance
	  • Suits
	  • Umbilical
	  • Heater

Conclusion

The use of free-flooding hot water suits provides a robust and simple approach that can be used over a wide range of water temperatures for long duration dives. In addition, variations in water temperature, depth, or duration have no impact on the diver-carried equipment. The system simply adapts to these changes with adjustments made on the surface to the hot water heaters' output temperature and/or flow rate.

This allows diver training to be focused on a single equipment configuration with no regards to water temperature, planned depth, or duration. The hot-water approach can also maintain the diver in the fully functional category without regards to water temperature, depth, or duration of the dive. The approach also provides the diver a high level of dexterity as glove types are easily adjusted as needs dictate. The approach is simple when compared to the passive approaches where one must determine the level of protection for the diver and their hands based on the anticipated exposure.

When topside support and deck space is limited, and/or the diver is untethered, the use of wetsuits or drysuits are the two alternatives. However, with these passive approaches the level of planning increases as the water temperature drops and the dive depth and duration increase. The dive planner needs to be provided with planning tools to develop a diver thermal exposure management plan. These tools can be developed from the work of Thalmann (1990) and Bradner (1985).

The wetsuit provides a simple and robust approach in water temperatures of around 25ºC (77ºF) and above. A high quality 6-7 mm wetsuit can provide more than 3 hours of exposure protection in this temperature range. The use of a wetsuit minimizes diver training and reduces topside support needs. However, the dive planner has to consider the temperature range for the complete profile of the dive. In addition, the limited operational range of the wetsuit needs to be fully understood by the planner.

When the exposure limits of the wetsuit are reached and the water temperature drops below 25ºC (77ºF), a drysuit with appropriate insulation and accessories can greatly extend the exposure range. As water temperature drops below 7.2ºC (45ºF), additional consideration needs to be given to the hands and feet to prevent NFCI. To protect the hands, a dry glove system is needed and ideally the glove system should not include a wrist seal. The feet will also need to be protected by additional insulation.

On dives with duration greater than one hour, the drysuit should be configured with a urine elimination system. In the technical diving community, the drysuit is typically equipped with an overboard dump system that utilizes an external catheter. However, this system is only available for male divers and the alternative to the overboard dump is an adult diaper.

Argon, as an alternate drysuit inflation gas, can extend the operational range of a drysuit system. Argon has a long history of use with recreational divers, working divers, and exploration groups. The Wakulla Karst Plains Project (WKPP) is exploring, mapping, and setting up hydrology monitoring stations in the cave systems of northern Florida. The WKPP is conducting dives to depths of over 91 m (300 ft) in 21ºC (70ºF) water with bottom times in excess of 5 hours and decompression times approaching 20 hours. The WKPP uses Argon as a suit inflation gas on all dives. In addition to the WKPP, the European EKPP project has been conducting dives with similar depths and durations but in colder 11ºC (52ºF) water. EKKP is also using Argon as the suit inflation gas (Jablonski, 2005).

Drysuits require a higher level of diver training and maintenance than the wetsuit or hot water suit. However, a well-trained and properly-equipped drysuit diver can carry out long duration dives over wide range of temperatures.

A first consideration in selecting the type of diver thermal protection is the range of temperatures, depths and anticipated durations. This, coupled with the size of the surface support platform, will dictate the type of equipment that can be accommodated and the methods that can be used to minimize the diver's thermal exposure. The resulting thermal exposure management plan should always keep the divers at a level of full functionality; which gives the diver some leeway in the event of unanticipated problems.

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