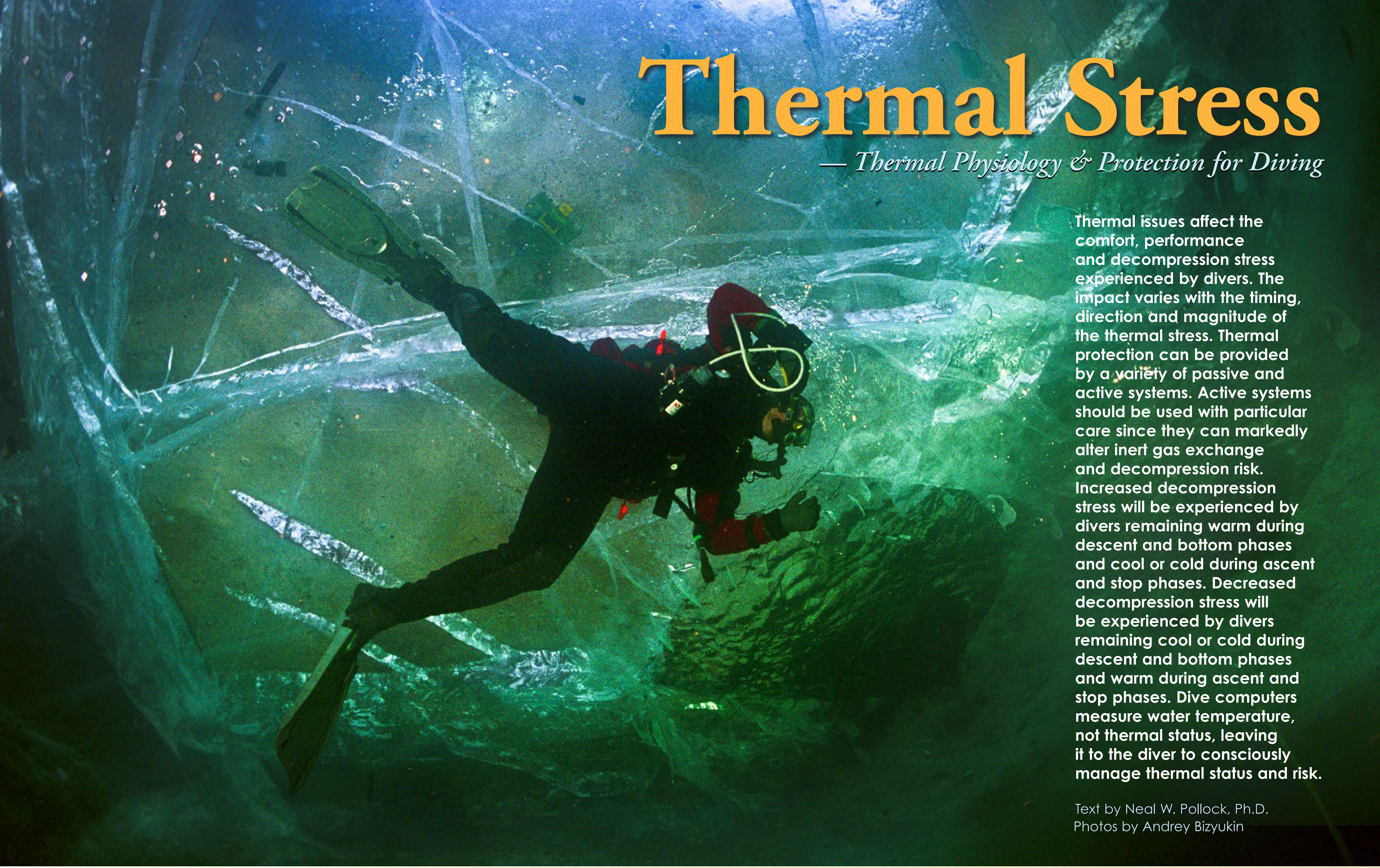

Thermal Stress

— *Thermal Physiology & Protection for Diving*

Thermal issues affect the comfort, performance and decompression stress experienced by divers. The impact varies with the timing, direction and magnitude of the thermal stress. Thermal protection can be provided by a variety of passive and active systems. Active systems should be used with particular care since they can markedly alter inert gas exchange and decompression risk. Increased decompression stress will be experienced by divers remaining warm during descent and bottom phases and cool or cold during ascent and stop phases. Decreased decompression stress will be experienced by divers remaining cool or cold during descent and bottom phases and warm during ascent and stop phases. Dive computers measure water temperature, not thermal status, leaving it to the diver to consciously manage thermal status and risk.

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Diving is conducted in thermal environments ranging from tropical through polar. While physical comfort and concentration and performance issues are often perceived as the top priorities, thermal status can also play a critical role in decompression risk. Thermal effects can either increase or decrease the net decompression stress, depending on the timing, direction and magnitude of the effect.

U.S. Navy test

The best demonstration of the fundamental relationships was provided by a study of 73 male U.S. Navy divers (37±6 years of age; 27.6±3.1 $kg \cdot m^{-2}$ body mass index) completing a total of 484 person-dives in an ocean simulation facility.[1]

Divers were fully immersed and exercising at the substantial rate of approximately seven times resting effort (seven metabolic equivalents [MET]) in a wet chamber during simulated dives to a depth of 37 msw (120 fsw). The bottom phase was followed by a long decompression (87 minutes) to accommodate increased bottom time in the event that the rate of decompression sickness (DCS) stayed low during the study. The water temperature was held constant (clamped) for two phases—descent/bottom and ascent/stop.

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Decompression risk

Clamp temperatures were 36°C (97°F), described as 'Warm', and 27°C (80°F), described as 'Cold'. Ultimately, the greatest decompression risk was experienced when the clamped conditions were warm for descent/bottom (promoting inert gas uptake) and cold for ascent/stop (impairing inert gas elimination). The lowest decompression risk was experienced when the clamped conditions were cold for descent/bottom (impairing uptake) and warm for ascent/stop (promoting elimination).

Big effect

The surprising result of the U.S. Navy study[1] was the magnitude of the effect. The 'Warm-Cold' combination had a 30 minute bottom time and yielded 22% DCS while the 'Cold-Warm' combination achieved an extended bottom time of 70 minutes that yielded only 0.1% DCS. While the decompression phase of the study dives was long in comparison with typical operational dive profiles, the study clearly shows that thermal status can have truly dramatic effects. Given this, it is important for divers to have a reasonable understanding of thermal physiology.

Major avenues of heat exchange

There are four primary avenues of heat exchange important in the diving environment—radiation, conduction, evaporation and convection.

Radiation represents the electromagnetic energy radiating from any object to any cooler object separated by space (air or vacuum). *Conduction* represents the heat flow between objects in physical contact. Insulation represents the inverse of conduction, that is, the resistance to heat flow. *Evaporation* represents the heat energy expended to convert liquid water to gaseous state. Evaporative heat loss results from humidifying inspired gases and the evaporation of sweat on the skin. *Convection* represents the heat flow through circulating currents in liquid or gas environment.

The typical concern in most diving environments is the minimization of heat loss. Even tropical waters can produce substantial cold stress over long exposures. Radiative heat loss is a relatively minor concern in diving. Radiative barriers have been added to the inside of some wetsuits and drysuits, but probably with limited benefit.

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Heat loss in water

Conduction is the primary avenue for heat loss in water. The heat capacity of water (density x specific heat) is >3500 times greater than air, yielding conductive loss rates 20-27 times greater than air. While 'cold' may be a bit extreme a descriptor for 28°C water,[1] it will produce substantial thermal stress for an unprotected diver since mean skin temperature is usually around 32°C. Protection against conductive losses is gained through improved insulation. A uniform distribution of an excellent insulator such as a vacuum space would be best, but persistent loft is a challenge in drysuits since hydrostatic pressure shifts gas to the highest point of a suit during immersion, effectively reducing the insulation layer elsewhere.

Evaporative heat loss from the skin is not a concern in high relative humidity environments. A fully saturated environment exists during unprotected immersion or in a wetsuit. A fully saturated environment develops very quickly in a sealed drysuit.

Convective heat loss can vary substantially, depending on the stability of the near skin microclimate. Drysuits provide a stable environment, wetsuit provide a reasonably stable environment if the design and fit effectively minimize water circulation. Convective losses can be substantial in a poorly fitting wetsuit.

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Unprotected cold water immersion

Even the modest protection of a poorly fitting wetsuit or drysuit moderates thermal stress for most divers. It is, however, possible that unprotected immersions or extreme expeditionary dives can produce significant stress. For that reason, extreme impacts should be understood.

Cold water immersion of an unprotected person can be described as a continuum of four phases.

Cold shock

The first is characterized by the initial immersion response or 'cold shock' that develops in the first two minutes. In this phase heart rate, respiratory rate and blood pressure rapidly increase and cerebral blood flow velocity decreases as hyperventilation reduces the carbon dioxide level in the blood. The impact of cold shock increases for unprotected immersion as water temperature falls below 15°C (59°F).

Wetsuits and drysuits will normally largely eliminate this phase from the normal diver experience.

Swimming failure

The second phase of unprotected immersion is characterized as short term immersion or 'swimming failure.' A rapid chilling of superficial skeletal muscles (conductive cooling) creates a crippling weakening. It is this phase that is most likely to kill unprotected swimmers that do not have sufficient buoyancy to keep mouth and nose clear of the water. Dive suits would have to be markedly inadequate for the conditions to see this with divers.

Onset of hypothermia

The third phase is described as long term immersion, when hypothermia might develop. The evolution of hypothermia will vary dramatically with thermal protection worn, total mass, surface-to-volume ratio, the amount of subcutaneous fat to serve as passive insulation, the amount of skeletal muscle able to generate heat through shivering, and water temperature. Core temperature is normally maintained at 37±1°C (98.6±2°F). Mild hypothermia is defined as a core temperature of 35-32°C (95-90°F). Even modest thermal protection suits can delay the development of hypothermia for long periods of exposure. Most divers who surface from a dive feeling cold, even if presenting with episodic or sustained shivering, are unlikely to have achieved sufficient core cooling to meet the definition of hypothermia. Regardless, severe discomfort and impairment can result from prolonged cold stress even without marked core temperature drop.

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Critical phase

The fourth phase describes the critical period when a victim is rescued from significant cold immersion. A combination of handling stress, loss of hydrostatic pressure secondary to removal from the water, and increased circulatory demands to accommodate postural changes can all act to produce 'circum-rescue collapse'.[2] The impaired cardiac function associated with high moderate (32-28°C [90-82°F]) or severe (<28°C [82°F]) hypothermia are more likely to be associated with collapse. It is critical that patient vitals are closely monitored through the removal and post-removal period since physiological collapse is possible. This would likely only be a consideration for divers in the direst conditions.

A post-exposure decrease in core temperature ('afterdrop') may follow the end of cold dive.[6] While afterdrop is typically not a problem, it is important to be aware that a person close to serious core temperature depression could be taken over the edge with afterdrop. This is extremely unlikely to be an issue in a typical diving scenario.

Thermal protection for cold water diving

Passive insulation can be provided by wetsuits or drysuits. Active insulation can be provided by electrically heating garments or hot water suits.

Standard foam neoprene is compressed by pressure, reducing the insulation and altering the fit.

The thermal protection of drysuit systems is generally provided by a three layer strategy. The base layer is hydrophobic to wick water away from the skin. In air environments the physical distance between the moisture and the skin limits evaporation and, by extension, evaporative heat loss. This is not the case in the high relative humidity environment of the closed drysuit. Instead, the water is wicked away from the skin to reduce conductive heat loss to the liquid. The mid-layer of the drysuit provides insulation, further reducing conductive heat loss. The outermost shell layer provides a

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barrier to reduce convective heat loss.

Drysuits may be made from a variety of thin membrane materials, standard neoprene, or crushed neoprene formed under greater pressure than standard neoprene. The insulation provided by shell suits is typically stable but modest thermal protection. As with wetsuits, the insulation of standard neoprene drysuits is compromised by pressure increase. 'Crushed' neoprene generally provides greater and more stable insulation throughout the typical diving range.

Trapped gas

The undergarments and trapped gas can provide the majority of the insulation in a drysuit system. Some garments with extremely high loft have been marketed.

Problematically, if these materials are easily compressed, they will perform better on the surface than when compressed by hydrostatic pressure during immersion. Thinsulate has been the closest to a standard in diving undergarment insulation for decades, but it has only partially satisfied thermal protection needs. Recent efforts have been directed at integrating rigid forms into garments to limit loft loss during hydrostatic compression to stabilize insulation layers.

Ongoing efforts are directed at impregnating aerogel into undergarments. Aerogel is a low density, highly porous silica matrix with extremely low thermal conductivity. The goal is to encapsulate the aerogel into a bat matrix of other materials to overcome the relative fragility and inflexibility of aerogel.

Argon is questionable

Argon has been promoted as a drysuit inflation gas to improve thermal protection. Theoretically, the 30% lower thermal conductivity could produce a 48% increase in suit insulation in comparison to air (1.92 vs. 1.30 clo, respectively).[5]

The argon fill did not improve skin temperature, core temperature or perceived thermal comfort

However, a double-blind field study found no benefit of argon vs. air. The argon fill did not improve skin temperature, core temperature or perceived thermal comfort.[8]

A similar lack of impact on core temperature or perceived thermal comfort was seen in a more recent study.[10] It is likely that hydrostatic pressure forcing the gas bubble to the highest point of the suit obviated the possibility of the gas forming a stable boundary layer over the skin and contributed to the lack of impact.

Another practical issue in using argon is that substantial volumes are required to fully flush air out of a suit. This can be a problem for the budget-conscious diver.

Limited usefulness

Combining argon with an undergarment that preserves gas channels may offer some improvement, but a significant benefit of argon use may be limited to long, expeditionary dives when small improvements in thermal protection may be meaningful. For most dives, a much greater thermal benefit is likely to be gained from improved insulating designs and materials.

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Heating

In-suit electric heating is now available for both wetsuits and drysuits. Battery-powered systems can provide multiple power settings and multiple zones. While these systems may substantially improve personal comfort, they also have the potential to increase decompression stress by promoting the uptake of inert gas when used during the descent/bottom phase of a dive.

A reduction in heat output, or worse, a complete heating system failure later in the dive would produce the 'Warm-Cold' situation shown to dramatically increase decompression stress in the U.S. Navy study.[1] Disciplined use of active heating systems could reduce the hazard, for example, by only turning it on at the end of the bottom phase.

Concerns

There are legitimate concerns with this approach. Reduced concentration and physical performance could result from inadequate thermal protection. The question as to whether the system will activate appropriately when required may be stressful. Finally, it could be that late activation will not be sufficient to provide adequate comfort and improve decompression outcome.

A compromise for systems that provide multiple heating levels

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would be to keep it on the lowest setting during the descent/bottom phase and then adjust it to a higher setting just before ascent. It remains to be seen if concerns over decompression risk will outweigh personal comfort and keep these devices compatible with decompression safety.

Little research

While few research data are available on the decompression hazard associated with electrically heated garments, there is a reasonable body of literature addressing similar concerns with hot water suits.

Primarily used in commercial operations, hot water is pumped into a wetsuit that distributes the water around the diver's body before it escapes to the environment. As an added benefit in deep dives, the heated water may pass through a heat exchanger to warm the inspired gas.

Hot water suits have been clearly associated with an increased risk of DCS in comparison with passive insulation.[4,9] A secondary concern is that actively warming the skin will effectively incapacitate the cold receptors that are predominant in the skin. This has been suggested to inhibit physiological response to respiratory cooling.[3] It is possible that a diver would not be aware of core temperature declines with skin temperature preserved at normal levels.

Monitering thermal status and decompression stress

Thermal stress is determined by the thermal protection worn, diver habitus and physical activity. It is not reflected by water temperature, which is the only thermal measure captured by existing dive computers. Current decompression algorithms do not assess thermal status, even though it can substantially influence decompression safety.

While real-time monitoring might one day allow for dynamic decompression algorithm adjustment, the best protection for current divers is a thorough appreciation of the hazards and thoughtful decision-making that favors safety, even if at the expense of comfort.

Efforts to avoid being warm during periods of inert gas uptake and cold during periods of inert gas elimination should be a minimum target. Remaining cool during the descent/bottom phase and somewhat warmer during the ascent/stop phase is optimal, as long as the warming is not achieved by physical effort that may also promote bubble formation. Increasing decompression safety buffers for thermal conditions that are less than optimal is good practice.

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