Why Argon?

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Introduction

This article addresses the question: "what is the best dry suit inflation gas?" Consideration of the physical properties of various alternatives leads to some interesting candidates from a purely theoretical standpoint, however the choice is narrowed when we also consider safety, economics, and practicality. It turns out that while argon is not the most insulating gas, it is the most practical choice. Nonetheless, the reasoning leading to this conclusion is subtle, and the answer is *not*: "Argon is a good insulator because it is dense." If good insulation simply resulted from gas density, then on every deep dive, we would notice a large improvement in insulation as we add gas to our dry suits to offset the compression of depth. In fact, gas density and pressure have little effect on the *conduction* of heat from a diver, so what works on the surface, works just as well below.

Clearly, suit inflation gas is only one of many factors affecting a diver's thermal protection. Other important points include the choice of dry suit undergarments, the types of gloves and mask worn, and even eating an adequate meal before diving to ensure a supply of metabolic heat. I will not address these issues, which are covered by Aspacher's point-by-point analysis of heat loss mechanisms that affect divers (Reference 1), and a review of the field experience in thermal protection given at the tek95 conference (Reference 2).

Theory

In addition to maintaining a stable insulation space between a diver's body and dry suit, undergarments serve a number of other important functions such as reducing convective transport of heat by the inflation gas. For my purposes, these effects are ignored, and the only heat loss mechanism considered is through conduction by the composite insulator formed by the underwear and inflation gas. From this restricted view, the underwear maintains a physical space of thickness t filled with gas of *thermal conductivity* K_{GAS} between the diver and suit. The underwear also has its own conductivity $K_{UNDERGARMENT}$, and conducts heat from the diver independently from the gas as a parallel loss mechanism.

Over the surface of the divers body, the resistance R of the composite insulator to the conduction of heat is expressed as the ratio of thickness to conductivity:

$$R = \frac{t}{K_{GAS} + K_{U.GARMENT}}$$

The larger the ratio *R*, the less heat a diver will loose to surrounding cooler water, so our objective is to increase the resistance to heat loss. For a fixed $K_{UNDERGARMENT}$, *R* can be made larger by either increasing thickness ***t***, or by decreasing the gas conductivity K_{GAS}. A diver can increase ***t*** by wearing a combination of thicker underwear and more weight to compensate for the increased insulation volume. Nevertheless, there are comfort limits --the doughboy look is not conducive to efficient motion. For a particular set of undergarments and equipment weight, divers can best insulate themselves from heat loss by choosing a suit inflation gas with a small thermal conductivity.

Before looking up tables of gas conductivities, we can gain some idea of which gases should perform well by considering the microscopic origin of the numbers displayed in the tables. With this physical insight, we can predict the top candidates.

Simply stated, the thermal conductivity of a gas is a product of factors, which either aid or impede the flow of heat. Roughly, the thermal conductivity K_{GAS} increases with the specific heat C_V of the gas molecules, and decreases with the square root of the mass ***m*** and cross-sectional size **σ** of the molecules. That is,

$$K_{GAS} \sim \frac{C_V}{\sigma\sqrt{m}}$$

This equation will serve as a guide, with the squiggle implying mathematical *form* rather than *exact equality*. Our goal is minimize the conductivity K_{GAS} by finding a gas where we minimize C_V while simultaneously maximizing ***m*** and **σ**. Details on how each of these three factors affect heat conduction are discussed on the page: Molecules .

When the conductivities of different gases are compared, the molecular specific heats and cross sections must be taken into account in addition to considering the masses of the molecules. So, for example, the effectiveness of argon as an insulator compared to air and helium mixtures is not simply due to argon's greater mass. If the conductivity of argon is compared with air (as in Table 1 below), the superior performance of argon is primarily due to its lower specific heat, rather than its greater molecular mass. On the other hand, argon's conductivity is much less than helium because of argon's greater mass and size --the two gases have the same specific heat.

You might think that gas conductivity K_{GAS} should increase with pressure because of the greater concentration of molecules available to carry heat energy in the dense gas. Although this seems reasonable, greater gas density also impedes the flow of heat by increasing the frequency of collisions between molecules. The random collisions scatter molecular motion away from the gradient of heat flow (from the warm diver to the cold water), canceling the density effects, and leaving only the residual proportionality constant as the factor of 1/**σ** in K_{GAS}, related to the molecular cross section.

Candidate Gases

So, where does theory lead us? We found that the gas with the smallest K_{GAS} should simultaneously have low C_V along with large ***m*** and **σ** . We can now see why hydrogen is the worst possible choice for an insulation gas: it has the lowest mass of all molecules, it is also a small, diatomic molecule giving it a large C_V and small **σ**, adding up to three strikes. With the additional exploding-diver hazard, H_2 is definitely "out." Helium is only slightly better than hydrogen due to its smaller size, greater mass and lower specific heat. Moving to the other extreme, from a purely physical standpoint, the insulation gas of choice would be large, massive, monatomic radon (Rn). But radon also has the additional potential to warm the diver due to its "hot" radioactive nature so, we cannot rely on physics alone to guide the search --we need to be practical. Moving away from radon, the next two massive, large, monatomic gases are xenon and krypton, which have great thermal properties, but at $1000 per standard cubic foot (scf) cost too much. Argon (Ar) comes next in order of the massive monatomics and is obviously a reasonable choice, so we'll set it aside for further consideration. Another class of candidates is suggested by the large mass of uranium hexaflouride (UF_6), with K_{GAS} a close second to radon. Unfortunately, UF_6 shares radon's health disadvantages and raises certain state security issues. Reasoning in a similar vein to how we guessed Ar should have a low conductivity, an agreeable cousin to UF_6 is found in sulfur hexafluoride (SF_6), which has actually been used as a suit inflation gas by the US Navy. Under the category of miscellaneous candidates is carbon dioxide (CO_2), which has also been used in Navy tests, because of the ability of closed circuit UBA to scrub any residual CO_2 from the swimmer's breathing gas. From a physical standpoint, CO_2 is a reasonable choice because of its large size and mass, however, its $\boldsymbol{C_V}$ is large due to triatomic structure. For similar reasons, small, non-chlorinated freons such as Freon14 (CF_4) should perform well, so we can include them in a short-list of contenders for the optimal suit inflation gas: Ar, CO_2, SF_6, and CF_4. Sulfur hexafluoride and Freon 14 might be eliminated straight away based on cost (20 to 30 times the price of argon per scf), however, we'll keep them around for the sake of argument.

Table I displays the conductivities of some alternative gases as a percentage of the conductivity of air, with He and H_2 included as examples of poor choices. The best inflation gas choices all have ratios less than one (100%), representing lower conductivities, and an insulation improvement over air. The thermal conductivities of the candidate gases are all less than air --the inflation gas for which all dry suit divers have a "feel." The entry for all nitrox mixtures (from 0% to 100% O_2) is the same as air due to the near identical conductivities of N_2 and O_2. It should be noted that the thermal conductivity of trimix is not simply determined by the fractional conductivities of the individual gas components! The details are beyond the scope of this article, but mixed gas conductivity follows a nonlinear mixing rule.

Note from the equation for *R* above, we can trade off the thickness t with the total thermal conductivity ($K_{GAS} + K_{U.G.}$) while maintaining the same thermal resistance. If undergarment conductivity is neglected, then a diver can get the same amount of insulation from air as argon if they increase the thickness of their underwear by about 50% (1 / 0.67 = 1.48) to cancel the higher conductivity of air. Realistically, when undergarment and water vapor conductivity are considered, the difference in thickness is not this large. Other comparisons between each of the gases can also be made by taking the ratio of the tabulated conductivities, because the factors due to air will cancel out. As another example, argon has a small fraction of helium's conductivity as seen from the ratio: K_{Ar} / K_{He} = (67 / 583) = 12%.

Table I **Gas thermal conductivities as a percent of the conductivity of air at 1ata and 300 K.**

GAS	Nitrox (0%-100%)	H_2	He	Ar	CO_2	SF_6	CF_4
K_{GAS} / K_{AIR}	100%	695%	563%	67%	62%	50%	62%

Table II **Absolute gas thermal conductivities *K* at 1 ata [cal/cm K sec], (Reference 3).**

GAS	Nitrox (0%-100 %)	H_2	He	Ar	CO_2	SF_6	CF_4	Rn
K_{GAS}	6.18	43.5	36.3	4.23	3.87	3.33	4.06	~ 0.97

All of the candidates have good thermal properties, but there are practical concerns that argue against CF_4, SF_6, and CO_2. CF_4 reacts chemically with natural rubbers and some plastics at high pressures. Furthermore, you get the same insulation quality from argon at 25 times lower cost, so CF_4 is not a good choice. Both SF_6 and CO_2 liquefy under the high pressures and low temperatures of suit inflation tanks. The gases are supplied as tanks with gas over a pool of liquid at the bottom, similar to the situation seen in butane lighters. In the case of CO_2, there have been anecdotal reports of rashes developing in humid areas, such as the armpits, due to irritation resulting from formation of carbonic acid by reaction of water and CO_2. The additional possibility of interaction of CO_2 with the diver's physiology should discourage carbon dioxide use (note that the Navy tests on CO_2 were conducted at shallow depths).
So, we are left with argon as the optimal suit inflation gas.

Field Practice

There may be psychological components to a diver's perception of warmth, where the use of argon initiates a positive feedback loop: "I'm using argon, so I must be warm...." But beyond these subjective aspects, the objective numbers in Table I show that argon could improve diver insulation by up to 50% compared to air. In reality, the full performance of argon is compromised by the conductivity of the diver's undergarments and the presence of gases in the diver's dress. ...uhm, that's air and water vapor.... So, in the field, argon's improvement of insulation will therefore be somewhat less than 33% maximum theoretical advantage predicted in Table I -- perhaps in the 10-20% range. Other points related to real-world applications are considered in Practical Argon
Finally, there is potential for interaction of suit inflation gas with a diver's physiology. In addition to irritation due to chemical reactions, there has been concern that the diffusion of inflation gas through the diver's skin could cause decompression problems due to the build-up of tissue partial pressure of the inert gas. It is clear that this concern is warranted for a diver breathing a slowly diffusing gas (such as air) immersed in a rapidly diffusing gas with low tissue solubility (such as helium). This situation is possible in pressurized habitats or chambers with BIBs, however, the opposite situation is what is typically occurs for sport decompression divers. Argon is both slowly diffusing and has high tissue solubility, so there is little risk of decompression problems resulting from argon counter diffusion in typical technical diving profiles. This applies to either SF_6 or CO_2 insulation gas as well.

Conclusion

Argon is a straightforward and inexpensive alternative to air for dry suit inflation. Just a few cubic feet (liters) of gas are required for most technical dives, depending on depth and diver ability. However, the trouble of an additional tank is not always justified in situations where air will suffice. Some argue against ever using argon when a thick set of underwear and more weight might do the job. And finally, suit inflation gas is only one of the many factors that impact a diver's overall thermal protection. Take a sensible, overall approach. Experiment, and then decide if argon is right for you!

References

(1) Aspacher, B. *IANTD Journal*, **94-3**, 26.

(2) *tek95 Thermal Protection Technical Seminar* proceedings, *aquaCorps* This was a tape distributed by *aquaCorps*. It's probably no longer available.

(3) Encyclopedie des Gaz (L'Air Liquide 1978).

(4) B. Hamilton recommends never using pure inert gases around breathing equipment. He notes that a 5% oxygen mix will sustain life in many instances.

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