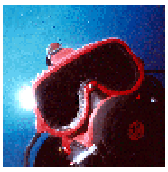

Why Argon?

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Introduction

This article addresses the question: "Given a dry suit, what is the best inflation gas?" Consideration of the properties of various gases leads to some interesting candidates from a purely physical standpoint, however the choice is narrowed when we are also concerned with safety, economics, and practicality. My objective is to show that while argon is not the best insulating gas, it is the most practical choice. Nonetheless, the reasoning 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 dry suit insulation with 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 (Ref. 1), and a review of the field experience in thermal protection given at the tek95 conference (Ref. 2).

Theory

In addition to maintaining a space between a diver's body and dry suit, undergarments serve a number of other important functions such as reducing the connective 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. The resistance R *per area* of the composite insulator to the conduction of heat is

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

The larger R is, the less heat the diver looses per unit area for a given water temperature. For a fixed $K_{UNDERGARMENT}$, R can be made larger by either increasing thickness t, or decreasing the gas conductivity K_{GAS}. The diver increases t by wearing a combination of thicker underwear and more weight. Nevertheless, there are comfort limits to contend with -- the "doughboy" look is not conducive to 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 gas can be written as a product of factors, which either aid or impede the flow of heat. Roughly, the thermal conductivity K_{GAS} increases with the specific heat $\boldsymbol{C_V}$ of the gas molecules, and decreases with the square root of the mass $\boldsymbol{m}$ 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*. When comparing the conductivities of different gases, 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 the argon is primarily due to its lower specific heat, rather than its greater molecular mass. On the other hand, the conductivity of argon 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 the conductivity should also increase with gas pressure because of the greater concentration of molecules available to carry heat energy. Although this seems reasonable, greater gas density also impedes the flow of heat by increasing the collision frequency of the molecules. The random collisions scatter molecular motion away from the gradient of heat flow (from the warm diver to the cold water), canceling the pressure effects, and leaving only a residual proportionality constant as the factor of $1/\sigma$ in K_{GAS}.

Now let's step back and consider the origin and effects of each of the factors in K_{GAS}. The amount of energy that can be carried away from a warm diver by a specific type of molecule is quantified by C_V. It is just a number that is related to the structure of the molecule, and remains constant for the range of diving temperatures. Throughout this discussion, I refer to the specific heat *per molecule*. When tables of specific heats are consulted, be careful to note the units of measurement used. For instance, if the specific heats are quoted as "per kilogram," then the fundamental nature of C_V is masked by a factor of density. The more complex a molecule is, the more ways it can store heat energy (by rotating and vibrating), and the larger C_V gets. Because K_{GAS} is proportional to C_V, we should look for simple gases with the smallest specific heat. The simplest gas molecules are single atoms: helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and radon (Rn). They all share the same specific heat due to identical structures. Furthermore, due to their spherical symmetry, the specific heat of the monatomic gases is the smallest possible. Single atoms have no way to vibrate or rotate, so they can only carry energy by moving. The next most complex molecules are diatomic. They are made of two atoms in molecules such as hydrogen (H_2), nitrogen (N_2) and oxygen (O_2) , which have the same specific heat about 5/3 times greater than the value for the monatomic gases. The larger value of C_V arises from the ability of the diatomic molecules to store energy by tumbling about their axes in addition to the energy they carry due to motion (vibration is not a viable energy storage mechanism for these molecules at diving temperatures). More complex molecules, such as carbon dioxide (CO_2) and sulfur hexafluoride (SF_6) have specific heats two or more times greater than the monatomic gases due to their complex geometries. Therefore, we prefer a monatomic gas for use as an insulator because of its relative inability to carry heat away from the diver due to its small C_V.

The specific heat of a gas is only one of the factors that influence its thermal conductivity. Both the mass and the cross-sectional size of the gas molecules reduce K_{GAS} as they get larger, which sways the argument in favor of large molecules. Note that the dependence of K_{GAS} on mass m is only as the reciprocal of the square root of the mass, which reduces the effectiveness of molecular mass in determining conductivity. The form of the mass dependence arises from the molecular velocities, which aid the transfer of heat as they increase. The low velocities of massive molecules reduce the rate at which heat is transferred by collisions, so we should look for massive molecules to reduce K_{GAS}. The size of gas molecules σ also influences the thermal conductivity by affecting the molecular collision rate. Larger molecules provide bigger targets to one another, and the likelihood of a collision increases, impeding the flow of heat away from the diver.

Candidate Gases

So, where does the 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 is 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 augment the theory with practicality. 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 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 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 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. The best inflation gas choices all have ratios less than one (100%), representing lower conductivities, and an insulation improvement over air.

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 300K.**

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], (Ref 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 cigarette lighters. There are efficient ways to transfer liquefied gases from cylinder to cylinder, involving heaters or snorkels, however, most divers would prefer to rely on a simple gas transfer hose. If you did use a fill whip to transfer gas from a liquefied source to a suit inflation bottle, the process would be slow and pressure in the suit bottle would be few hundred psi at most. Even if you could transfer liquefied gas to your inflation bottle, the possibility of shooting liquid into your suit should discourage you from doing this. The extreme pressures and low temperatures present at depths in excess of 500 ft could also cause a number of problems with SF_6. The gas in the diver's suit would tend to revert to liquid, and the equilibrium vapor pressure of the gas over liquid in the inflation bottle would not be sufficient to build interstage pressure for delivery through a regulator. 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).

Actual Practice

So, we are left with argon as the best suit inflation gas. In the field, argon's reduction in the thermal conductivity of a diver's dress will be somewhat less than 33% advantage predicted in Table I --perhaps in the 10-20% range. Setting up an argon suit inflation system is simple, and cheaper than a new set of undergarments. Many divers use an old regulator first stage and a pony bottle, while others purchase a complete inflation system. A word of caution: a pressure relief valve should be installed on an unused low-pressure port of the inflation regulator. If first stage freezes, or the high pressure seat fails, the low pressure side of the system will not be brought into high pressure service--resulting in a blown inflation hose--at least. As a back-up inflator on an air or nitrox dive, the low-pressure hose from the diver's buoyancy compensator should be detachable and able to reach the dry suit inflation port. The addition of a low-pressure hose to a nitrox stage could work for a back-up on a trimix dive, but this increases system complexity.

Argon fills are available at many technical facilities, and they are easily done by the diver with a gas transfer whip. There is, of course, no need for the cylinder to be argon-clean! Contemplation of the number of pre-filled small suit inflation bottles required to support a dive trip should lead to self-sufficiency. The North American CGA #580 fittings for argon cylinders are the same as other important inert diving gases (including Ne, N_2, and He). For world-travelers, the common denominator in high pressure gas fittings are the *National Pipe Thread* (NPT), and *British Standard Taper* (BST). As long as you have adaptors to these threads, gas bottle fittings can be obtained locally. Some of the other suit inflation candidates require fittings that are not available at every welding shop, which are a traveling gas diver's best friend. With some planning, it is easy to arrange to pick up argon and other gasses, even in remote areas. Without a traveling booster, it's best to take the entire supply cylinder to the site, but even a pony bottle will usually allow a few dives per fill.

There are many placement options for the inflation gas bottle. Rigging as a stage, or attached upside down to the back plate are likely the cleanest options that allow easy access to the valve. Incorporating the inflation gas into the diver's dress independent of the scuba unit has a number of safety advantages. A pocket on the diver's hip is one method for accomplishing this. Should the diver doff their set on the surface to expedite getting into a small craft, the inflation gas stays with the diver --an important consideration if a large weight belt is worn. An additional reason for integral suit gas placement is that if the need for in-water recompression arises, then the afflicted diver can get back into the water with a harness for therapy stages without the struggle of donning a full set. Another safety issue arises if the diver is using a helmet or full-face mask with a dry hood or neck dam above a dry suit inflated with argon. If much argon leaks above the neck seal, into the diver's oral/nasal, then severe narcosis or asphyxiation could result from inspired argon. While we're on the topic of suffocation, note that user vigilance along with proper cylinder labeling and gas analysis is essential to minimize the risk of tragically mistaking inflation gas for breathing media (Ref. 4).

There are psychological components to a diver's perception of warmth. Argon might be regarded as the start of a positive feedback loop: "I'm using argon, so I must be warm...." Beyond the subjective aspects of argon's insulation, there are the objective numbers in Table I, which for example, shows that argon should 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 other gases in the diver's dress (...ah...that's air and water vapor....). Residual atmospheric air should be purged before diving by inflating and venting the dry suit a few times with argon to reduce heat loss due to the comparatively high conductivity of air. For shallow dives, purging by a couple full inflations and dumps is particularly important for insuring that your suit is actually inflated with nearly 100% argon. Water vapor from perspiration will condense in the fabric of the underwear, increasing the underwear conductivity and diver heat loss. Steps should be taken to minimize perspiration, or a vapor barrier should be employed between the diver and the insulating undergarments.

As with breathing, venting suit gas will always actively transport heat away from the diver. Obviously, it is necessary to vent during a controlled ascent, just remember to tighten the suit dump valve a bit for decompression stops to avoid accidental loss of warm gas. Not only does the warmed gas leaving your suit take heat along with it, the energy required to warm any replacement gas could have been better used somewhere else.

Finally, it should be noted that there is the potential for interaction of the inflation gas with the diver's physiology. In addition to irritation due to chemical reactions, there is 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), however, the opposite situation is what is actually used in the field. 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 profiles. This applies to SF_6 and CO_2 as well.

Conclusion

Using argon is a straightforward and inexpensive alternative to air for dry suit inflation. Just a few standard cubic feet of gas are required for most technical dives, depending on depth and suit operator ability. However, the trouble of an additional tank is not always justified in situations where air will suffice. Some would argue against ever using argon when a thick set of underwear and weight harness will do the job. Suit inflation gas is only one of many factors impacting a diver's thermal protection --you decide if argon's right for you.

References

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

(2) *tek95 Thermal Protection Technical Session* 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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