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Research Article

Neutrally Buoyant Ergonomic Segmented Glass-Ceramic Composite Chocobar K4 Diving Suit with Superior Thermal Protection

Garrett Sabesky, Codi Clark, Andrew Waldron, Jeffrey Catterlin, Emil P. Kartalov*

Department of Physics, Naval Postgraduate School, Monterey, California, USA

ABSTRACT

Hypothermia is a serious health hazard for divers, as it can lead to unconsciousness, organ damage, and eventually death. To lessen the heat loss in water, divers typically wear bubbled neoprene wetsuits. However, this thermal protection worsens with depth as the air bubbles in the neoprene shrink under the elevated pressure. Thicker neoprene provides more thermal protection but is less flexible and thus fatigues the wearer more quickly. To solve this problem, we developed the K1 suit, which featured composite plates fitted to the inflexible areas of the body. The plates contained hollow glass microspheres embedded in silicone cured in 3D-printed molds designed from 3D body scans. The K1 combined the ergonomics of a 3 mm suit with thermal protection superior to a 7 mm suit. Next, adding a further outer layer of ceramic composite produced the K2 suit. The K2 increased thermal protection and improved ergonomics and handling by offering constant neutral buoyancy. However, both K1 and K2 used diver-specific molds, which made fabrication difficult and expensive. Hence, we developed the Chocobar–universal flexible composite plates that can be custom-trimmed to fit any diver. Our first Chocobar suit, the K3, was faster and easier to make, featured two layers of Chocobar glass composite, and demonstrated the best thermal protection so far (~4.5°C better than a 7/6 mm suit at depth). However, K3 suffered from excessive buoyancy, which necessitated extra ballast and worsened handling. Hence, we developed the K4 presented herein. K4 features two composite layers (outer ceramic and inner glass), constant neutral buoyancy, improved handling, minimized ballast, and high thermal protection (+3°C better than a 7/5 mm suit at depth). Hence, K4 is overall the best suit in this series. Hence, the K4 should be of great interest to diver suit technology developers and to commercial, recreational, and military divers.

Keywords: Ergonomics; Microspheres; Buoyancy; Diving; Cold; Hypothermia; Micro particles; Glass; Ceramics; Manufacturability

INTRODUCTION

Sea water has 24x the thermal conductivity and 4x the heat capacity of air [1]. So, even highly adapted sea mammals experience 4.5x faster heat loss in water than they do in air [2]. That heat loss leads to hypothermia even faster with human divers. After 15 minutes in 5°C water, or 1 hour in 10°C water, a diver would enter hypothermiaas his core temperature would fall below 35.5°C. Hypothermia is a serious hazardous condition that can lead to loss of consciousness, organ damage, and eventually death. Physical conditioning cannot fully compensate for the heat loss [3-7]. Hence, thermal protection is a necessity and is the only way to extend diver persistence time in cold water. Typical thermal protection is provided by a wetsuit, stitched and/or glued together from tailored pieces of neoprene. The neoprene is bubbled with air during manufacture because air is a very good thermal insulator. It is also easily compressible, which results in good flexibility of the material. The material is sandwiched between two thin layers of cloth, to keep the neoprene together mechanically and help prevent ruptures. Thicker suits offer more thermal protection. In 5°C water, a 3 mm neoprene suit extends the time to hypothermia from 15 minutes to 1 hour, while a 5 mm suit extends it to 1.5 hours [6]. However, thicker neoprene is less flexible. More effort is required to produce the same movements, which fatigues the diver more rapidly and decreases the amount of useful work that can be done during the same dive. Consequently, the thickest single suit on the market is 8 mm, while US Navy divers typically use 7/6 mm neoprene suits (7 mm chest, 6 mm limbs) in a tradeoff between protection and ergonomics. If movement is not a priority, a diver might use a Long-Johns-style combo suit which features two pieces (a sleeveless pants/torso and a long-sleeve jacket) that overlay on the torso and provide effective 15/7 mm protection. This style of

Correspondence to: Emil P. Kartalov, Department of Physics, Naval Postgraduate School, Monterey, California, USA, E-mail: epkartal@hotmail.com

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suit is currently the warmest on the market, but the protection is gained at the heaviest price in ergonomics and handling.

Thicker neoprene suits are also more positively buoyant, so to sink, the diver must equip more ballast to compensate. For example, at the surface, a 3 mm wetsuit will require 2 kg ballast, while a 7 mm wetsuit will require 8 kg ballast. The additional mass is traditionally worn as squarish lead weights hanging on the diver's belt. This is uncomfortable as the mass is poorly distributed. It also produces a straightening phenomenon, wherein the Archimedes force center is higher on the body than the gravitational center of mass. The result is a net torque around the center of mass of the diver that strives to position the diver vertically up. Divers must compensate for this effect by vigorous kicking downward when they are leaning forward, to produce a counter torque and help keep the diver horizontal for swimming. The extra effort contributes to fatigue and reduces the useful work done in the water. Hence, excessive positive buoyancy worsens ergonomics and handling. Furthermore, the compressibility of the air inside the neoprene means that buoyancy will decrease with depth. This would normally improve the above buoyancy problem, but it also interferes with the diver's ability to maintain depth. For example, a 3 mm wetsuit typically requires 1 kg of ballast at depth, instead of 2 kg at the surface, while a 7 mm wetsuit requires typically 2 kg of ballast at depth, instead of 8 kg at the surface. The buoyancy deficit at depth is compensated for using a (BCD) Buoyancy Control Device, which is worn as a vest and contains an inflatable bladder connected to the diver's breathing air tanks. Inflating or deflating the BCD as needed helps adjust the overall buoyancy of the diver, but it requires attention and it uses up breathing mixture, which shortens the available useful time under water. Overall, thicker neoprene suits incur significant sacrifice in ergonomics compared to thinner suits.

The compressibility of air inside the neoprene of the wetsuit also means that its thermal protection degrades with increasing depth, as increased ambient pressure makes the bubbles shrink and decrease the thickness of the neoprene [8]. Laboratory testing has demonstrated that 8 mm neoprene from a top-of-the-line commercial wetsuit loses ~50% thermal insulance at 30 msw, compared to the one at sea level [9]. This loss significantly shortens the available time at depth, compared to the time in the water at the surface. To address this problem, we developed a composite material made of hollow glass microspheres embedded in thermally cured silicone polymer. Laboratory testing demonstrated that the composite maintained its thermal insulance with applied pressure and was more thermally insulative than neoprene of the same starting thickness [9]. Next, the composite was used to build the K1 suit by thermally curing the material in polycarbonate molds that had been 3D printed in shapes matching the segmented 3D scans of the body of the diver [10]. Then the composite segments were attached to a 3 mm neoprene wetsuit/undersuit in tailored external pockets glued to the undersuit. The segments were tailored to cover the inflexible parts of the body, while the joints were only covered with the 3 mm neoprene of the undersuit. As a result, K1 had the flexibility and ergonomics of a 3 mm suit. Field tests of K1 showed that its thermal performance bested the one of a commercial 7 mm suit. Hence, overall, K1 offered superior flexibility and thermal protection, while also offering a constant buoyancy. On the other hand, K1 had significant positive buoyancy.

To address this issue, we developed the K2 suit, which featured an extra layer of composite made of solid ceramic microspheres in silicone [11]. This increased the thermal protection and changed the overall buoyancy to near neutral, which decreased the needed ballast weight, improved the overall weight distribution, and improved ergonomics and handling, while maintaining the great flexibility of a 3 mm suit. Field tests showed satisfactory thermal results and confirmed the ergonomics gain. While K1 and K2 were highly successful both would be difficult to manufacture commercially, because they would require personalized 3D scans and molds for each diver. While offering the best possible fit, this would make the suit expensive to produce. One potential solution would be to manufacture a library of sizes and then fit each diver through computerized component sizing calculated from the body scan, essentially assembling a custom suit from ranges of standardized sizes, body part by body part, to produce a good individual fit at reasonable cost [10,11]. This could work at scale, but the wide biological variability in sizes and body proportions, and the required large inventory would require a large initial investment. An alternative approach is to devise a universal cast fabrication technique, and then only do the individual trimming, sizing, and fitting during the tailoring process. Accordingly, we developed the Chocobar technique [12]. It involves segments built as 2D arrays of truncated square pyramids, whose dimensions are chosen in such a way that bending the segment produces a curved piece of preselected radius of curvature. Body measurements showed that the human body has a bimodal distribution of radii of curvature of the different parts, so just two Chocobar designs would be sufficient to provide for virtually all surfaces that need to be covered in a segmented dive suit. The respective molds were designed, 3D printed in polycarbonate, and used to cast glass composite Chocobar segments. The segments were then trimmed to fit the diver wearing a 3 mm neoprene suit, and then attached to the suit in external pockets glued to the outside of the 3 mm suit, using the same general technique as for the K1 and K2 suits.

The glass composite segments were arranged in two layers per pocket, to maximize the thermal protection. The resulting suit, the K3, was field-tested and showed the best-to-date thermal protection in the series (+4.5°C compared to a 7/6 mm), while offering the same 3 mm flexibility. On the downside, K3 had high positive buoyancy, which required 13 kg of lead ballast, while a typical 7/6 mm neoprene suit only requires 6 kg. To address the buoyancy disadvantage of the K3, we developed the K4 suit described herein. Briefly, the same Chocobar technique12 was used to mold composite segments, which were then attached in external pockets to a 3 mm suit by the same gluing and aqua-sealing techniques [12]. However, the starting undersuit was not custom-built but ordered commercially to help streamline manufacture and to show explicitly that commercial suits could be upgraded using our techniques Furthermore, the undersuit features a detachable hood, which was upgraded in the same way as the rest of the suit. Finally, each pocket contained an inner hollow-glass composite Chocobar segment and an outer solid-ceramic composite Chocobar segment, resulting in near-neutral buoyancy. This solved the buoyancy problem of K3. The resulting improvements in ergonomics were achieved at the cost of somewhat lower thermal protection compared to the K3. Thus overall, the K4 is the best suit so far in the series and should be of great interest to developers of diver suit technology, as well as to military, commercial, and recreational divers.

MATERIALS AND METHODS

IRB approval

Field test plans for the project were initially approved in 2020 by the Institutional Review Board (IRB) at the Naval Postgraduate School (NPS). More recently (February 2024), the project was reviewed again and given the operational exception.

Molds and casts

Ceramic Molds were designed (Figures 1A and 1B), for two types of Chocobar arrays: R1=50 mm (Figure 1C), and R2=250 mm. The designs were 3D printed in polycarbonate (Figure 1C), using a Fortus 400 mc 3D printer (Stratasys, Eden Prairie, MN, USA). Sylgard 184 (Dow Corning, Midland, MI, USA) prepolymer was mixed with K1 hollow glass microspheres (3M Corp.) for the glass composites, in ratios in grams of Monomer:Crosslinker:Glass=90:9:10, inside 300 mL jars in a planetary mixer (ARE310, THINKY, Japan) for 4 min at 1500 rpm,. W610 solid ceramic microspheres (3M Corp.) were analogously mixed for the ceramic composites, but in the mass ratios in grams of Monomer:Crosslinker:Ceramic=90:9:120. The resulting mixtures were degassed for 1.5 hours at 0.013 mbar in a large dessicator vessel attached to a mechanical vacuum pump. Next, the degassed mixtures were poured into the Chocobar molds and left to open air to degas passively for another 1 hour, which improved small bubble elimination (compare casts in Figure 1F left/right=with/without the extra hour). Then the lids of the molds were installed and clamped down by C-clamps (Figure 1D). This let excess prepolymer escape from the vents at the top of molds (Figure 1D), ensuring a snug fit of the lid to the mold and correct shape for the cast. The filled closed clamped molds were then cured in a Forced Air Oven (VWR) at 80°C for 2 hours. Then the molds were allowed to cool down to room temperature for at least 1 hour. Cured flash was removed from the lids. Steel chisels were used between mold and lid to pry open the molds (Figure 1E). The Chocobar casts were then extracted from the molds and deflashed. The casts were checked against a light source (Figure 1F) to identify any remaining large air bubbles that formed during the curing process. If such were found, they were removed by mixing corresponding uncured material, using it to fill up the air bubble, and then curing the result again in the 80°C oven for 2 hours.

Suit assembly

A commercial custom 3 mm suit was ordered from 7TILL8 (www.7till8.com) using 16 measurements of Diver A. The suit featured a well-tailored shape, a detachable hood, and a cross-chest zipper for entry. It served as the undersuit base for the construction of the K4. The Chocobar composite segments were organized in pairs (bottom glass, top ceramic) and trimmed to fit Diver A. Matching pieces of 2 mm closed-cell neoprene were tailored accordingly to serve as external pockets to contain the composite pairs (Figure 1G). The pocket material was glued to the undersuit using neoprene cement. Stitching was added where possible, to improve strength of the seams. Aquaseal was then applied to the glue lines/seams to strengthen them. The helmet/hood was similarly constructed (Figures 1H and 1I). This completed the suit and made it ready for field trials (Figure 1).

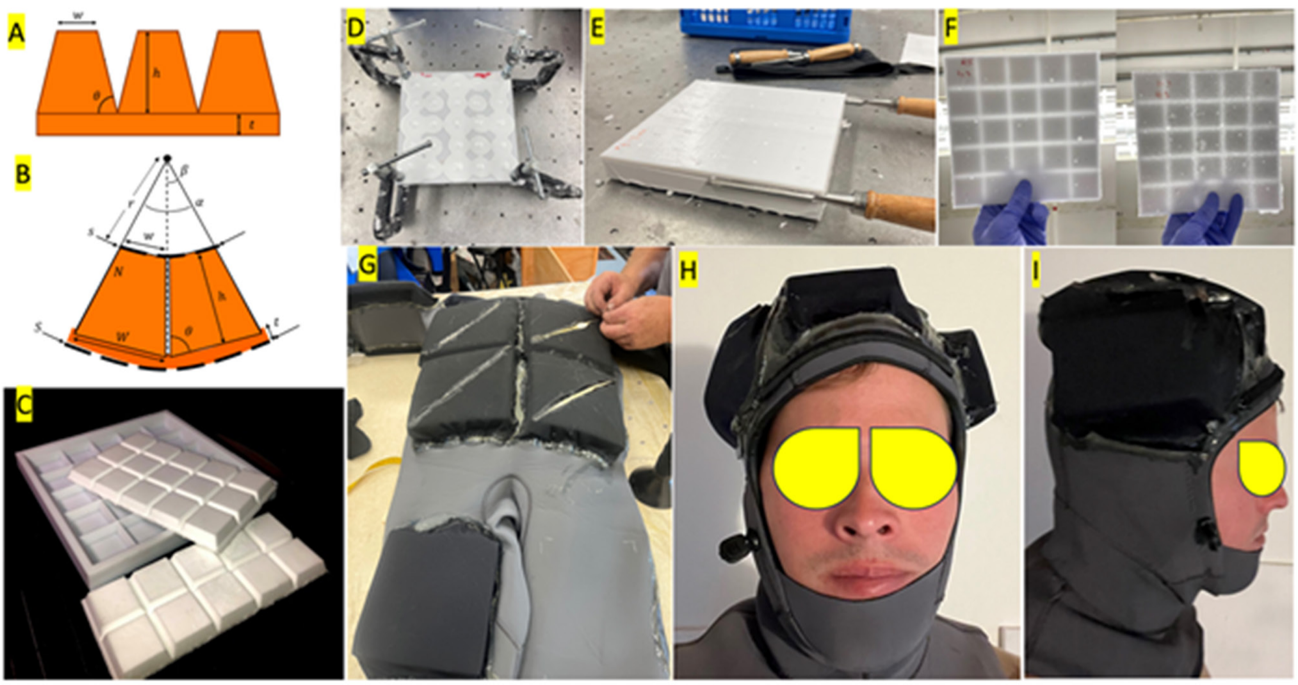

Figure 1: Design and fabrication, The Chocobar pattern (A,B) was designed for the two required curvatures (R1=50mm and R2=250mm), resulting in respective molds and casts (C). Degassed prepolymer mix was poured in a mold and sealed by clamping the lid using C-clamps (D). Excess mix was allowed to escape through vents on the lid (E), producing flash that was removed after thermal curing and cooling. Trapped air bubbles (F) were identified and refilled with fresh prepolymer mix, then cured again. The casts (C) were trimmed, fitted to the grey undersuit, and secured to it in external pockets (G) made of black 2mm closed-cell neoprene cemented to the undersuit. Stitching was used where needed. The stitches and cement lines were then Aquasealed. The helmet (H, I) was constructed analogously, with the added condition to allow the mask strap around the head and ventilation for the ears. The yellow "spectacles" (H, I) were added to maintain privacy.

Buoyancy calculation

The specs from the manufacturer (3M Corp.) indicate effective density of 0.125 g/cm^3 and 2.4 g/cm^3 for the K1 hollow glass microspheres and the W610 solid ceramic microspheres, respectively. Also, the density of Sylgard 184 is 1.02 g/cm^3. Previous measurements9 indicated that the maximal practical volumetric concentration of the glass microspheres in silicone is ~53% vol. Mass and density ratios then indicate that the solid ceramic composites were prepared at ~33% vol. Then, the effective density of the combination of two identically shaped plates (one with hollow glass and the other with ceramics) would be (0.53 x 0.125+0.47 x 1.02+0.33 x 2.4+0.67 x 1.02)/(1+1)=1.010 g/cm^3. For comparison, the saltwater density is 1.025 g/cm^3.

Biometric data

For each diver participating in the field tests, biometric data was collected using ES-26M-W Smart Body Analyzer (FITINDEX, fit-index.com). The measurements were taken in the recommended "athlete mode", consistent with a subject of at least 18 years of age, engaging in more than 6 hours of intense aerobic activity per week, and having a resting heart rate below 60 bpm. The anonymized results are presented in (Table 1).

Table 1: Biometric data for divers.

Biometrics	Diver A	Diver B	Diver C	Diver D
Weight, kg	87.5	92.85	102.6	80.6
BMI	27	28.7	28.4	27.2
Body fat, kg	15.1	16.3	24	21.7
Fat-Free Body Weight, kg	74.3	77.75	77.9	63.1
Subcutaneous fat, %	12.4	13.3	20.7	18.7
Viceral fat	10	11	11	10
Body water, %	61.3	60.5	54.8	56.5
Skeletal muscle, %	54.9	54.1	49	50.6
Muscle mass, kg	70.6	73.9	74.1	60
Bone Mass, kg	3.71	3.89	3.9	3.16
Protein, %	19.4	19.1	17.4	17.9
BMR, Kcal	1974	2049	2054	1733
Metabolic age, years	29	28	37	30

Field Testing

The field test dives were conducted at San Carlos Beach, Monterey Bay, California. In each dive, Diver A wore the K4 suit, while a second diver wore a commercial dive suit. In each dive, the two divers maintained the same depth and close proximity (<0.9 m). OM-CP-PRTEMP140 dataloggers (Omega Engineering, Norwalk, CT) were used to record the pressure and temperature digitally and automatically, at 1 sec internals for the first test, and at 10 sec intervals for the rest. Each diver wore a logger under his suit at the breastbone, and another attached externally to his BCD. The pressure data was converted to depth data, while the temperature data was used to calculate the temperature difference between the inside and outside of the suit, for each diver.

RESULTS AND DISCUSSION

The K4 is the fourth suit in the K-series, the K4 was fabricated starting from a commercial 3 mm suit that was tailored to Diver A's measurements and included a detachable hood and a cross-chest zipper. Onto this commercial suit, external pockets were added to house two Chocobar composite plates trimmed and tailored to the respective body area. The outer plate was made with W610 solid ceramic microspheres, while the inner plate was made with K1 hollow glass microspheres, both types embedded to volumetric saturation in Sylgard 184 to produce the respective Chocobar composite plates. Consequently, the composite plates were easily manufactural and readily bendable to the required body curvatures, while the effective density of the overall composite was very close to the density of seawater. Compared to the previous suits in the K-series, the K4 also features the detachable hood upgraded with double composite plates (glass/ceramic) as was done with the rest of the areas of the suit. In contrast, previous suits did not feature specialized helmets, but the divers instead wore commercial 3 mm neoprene hoods. The K4 helmet was constructed by adding the Chocobar pieces in external pockets, while care was taken to leave space for the strap of the dive mask. If the ears are covered with composite protection in future iterations, the mask strap will have to be lengthened, while extra care must be taken to prevent outer ear squeeze, as the wearer must be able to remove air from that region to maintain equilibrium. Once completed, the K4 suit was field-tested at the San Carlos beach in Monterey, California. Diver A wore the K4 while a second diver wore a commercial suit for comparison under the same field conditions. These suits and divers varied among the trials and are accordingly described in the respective subsections below. Their anonymized biometrics are listed in Table 1. The field data were collected using automated dataloggers that digitally recorded ambient pressure and temperature. Each diver wore one logger over the breastbone under the suit and another logger attached externally to his BCD. That allowed the calculation of depth from the pressure data and the calculation of temperature difference between the inside and the outside of each suit.

In Field Test #1, Diver A wore the experimental K4 suit. Diver B wore a commercial Xcel Hydro Flex 7.6 neoprene wetsuit, which had 7 mm on the chest and back, and 6 mm on the arms and legs. This suit did not have an integrated hood; instead, Diver B wore a separate hood tucked into the suit. As Diver A was donning the K suit, a seam failed in the arm, producing a hole of approximate size of 25 mm. The issue was partially mitigated by the application of duct tape. After the dive, it was also determined that some of the seams were not yet Aquasealed. Overall, these factors produced unwanted water penetration. Figure 2 shows the plotted results. It is evident that the K4 initially outperformed the 7 mm initially by at least +2°C. However, inside the water, the leaks degraded the thermal performance of the K4 suit (Figure 2).

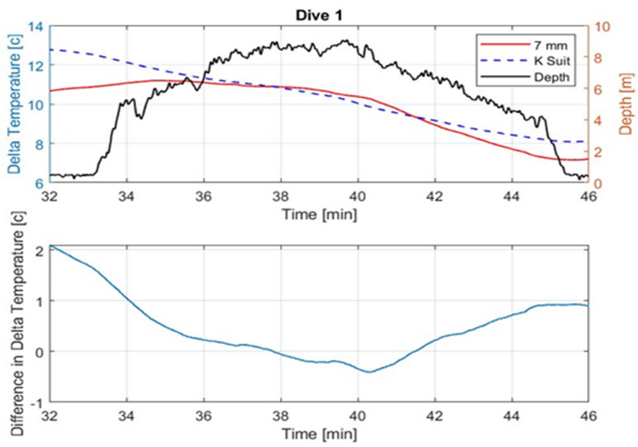

Figure 2: Results from Field Test #1. Diver A wore the K4 suit, while Diver B wore a commercial 7 mm. **Note:** ( ) 7 mm; ( ) K-Suit; ( ) Depth.

In Field Test #2, As this was the next day after test #1, there was no time to apply Aquaseal, but the hole in the seam of the arm on the K4 had been repaired by careful stitching. The second diver, Diver C, wore a Long-John-style double-layer 7 mm neoprene suit, which includes a Farmer-John-style sleeveless overall and a sleeved jacket worn over it. This produces effective protection of 14 mm on the chest and back, while the limbs have 7 mm protection. This is extreme neoprene protection purchased in a tradeoff of ergonomics. The experimental results are shown in Figure 3. The Long-John outperformed the K4, including at depth, which would be surprising, except for the persisting problems with sealing of the K4 seams (Figure 3).

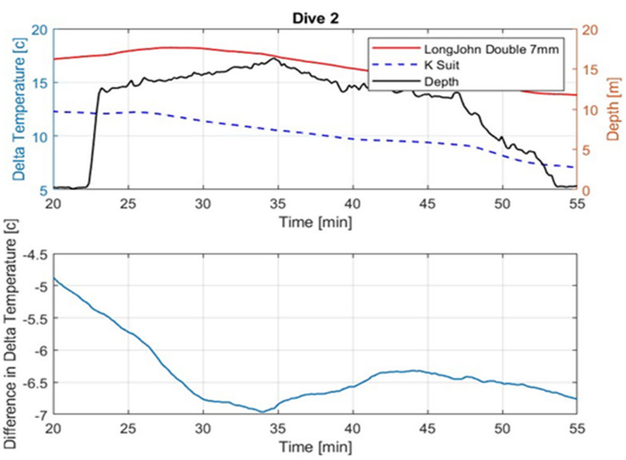

Figure 3: Results from Field Test #2. Diver A wore the K4 with patched up arm seal, but still no full Aquaseal. **Note:** ( ) Double 7 mm; ( ) K-Suit; ( ) Depth.

In Field Test #3, The K4 had the ripped seams Aquasealed Diver A wore the K4 suit. Diver D wore a SCUBA Pro Everflex 7/5 mm wetsuit, which had 7 mm protection on the chest and back, and 5 mm protection on the arms and legs. The results (Figure 4) show that the K4 consistently outperformed the 7/5, by as much as +2°C, except for at the very beginning of the dive. This observation is consistent with the explanation that shrinkage at depth significantly degrades the thermal protection of traditional neoprene suits. On the other hand, some protection degradation over time was recorded with the K4 as well, which was explained by more water leaks that were detected after the dive.

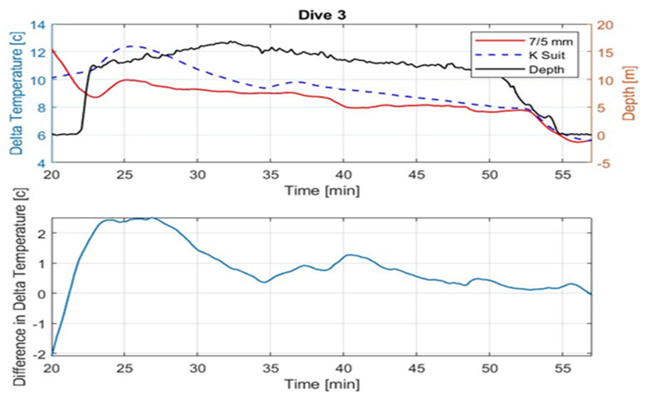

Figure 4: Results from Field Test #3. Diver A wore the K4, while Diver D wore a commercial 7/5 mm suit. **Note:** ( ) 7/5 mm; ( ) K-Suit; ( ) Depth.

In Field Test #4, The persisting issue with water leaks necessitated a complete overhaul with Aquaseal of all seams that showed insufficient coverage. The now fully repaired K4 was tested again under the same conditions as with Field Test #3: Diver A wore the K4 and Diver D wore the Pro Everflex 7/5 mm wetsuit. The results (Figure 5) show that K4 consistently outperformed the 7/5 mm suit by an average of +3°C at depth (Figure 4).

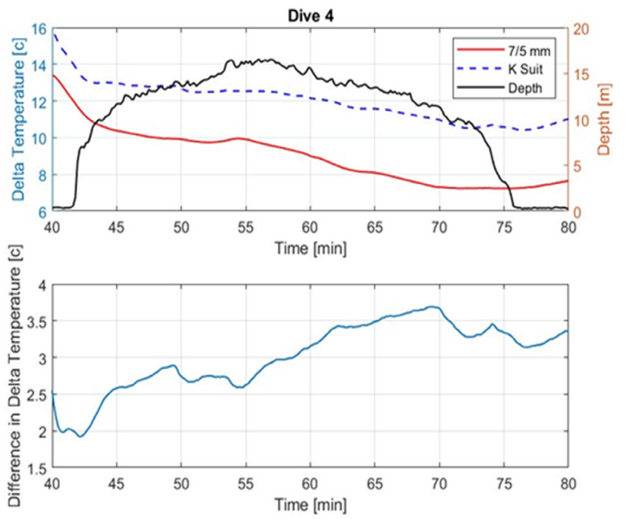

Figure 5: Results from Field Test #4. After extensive resealing with Aquaseal, the K4 was tested in the same way. **Note:** ( ) 7/5 mm; ( ) K-Suit; ( ) Depth.

The results suggest that the previous problems with performance must have been due to leaks and insufficient Aquasealing of the seams. Field Test #4 decisively shows that when properly sealed, K4 would offer consistent and significant advantage over conventional 7 mm suits in use. This interpretation is also reinforced by the comparison in time evolution of tests #3 and #4, where the temperature drop for K4 with respect to the ambient water over time is -4.5°C and -2.5°C, respectively. Such a large difference indicates a corresponding difference in the quality of the seals. By comparison, the 7/5 mm suit experienced a drop of -5.5°C during the same dive, so the repaired K4 clearly offers a flatter response and less depth dependence (Figure 5).

Figure 6 shows the K4 in action. The neutral buoyancy decreases straightening torque, makes it easier for the diver to maintain horizontal orientation, and decreases the amount of required ballast. The mask strap fits under the line of the composite pockets. Furthermore, Diver A consistently reported that the K4 suit handles as a 3 mm suit in flexibility and effort to move, while the more even distribution of mass produced a noticeable improvement in handling. In addition, the required ballast for the K4 was less than 6 kg, which is less than the one required for typical 7 mm suits, and significantly less than the one required for even thicker suits. To recap, the K4 consistently and significantly outperforms 7mm suits in thermal protection (on average +3°C at depth), depth response, ergonomics of flexibility (3 mm equivalent), and ergonomics of mass distribution (neutrally buoyant). The K4 protection is somewhat decreased compared to the K3 (+3°C *vs.* +4.5°C), which makes sense in view of the ceramic/glass *vs.* glass/glass composite. However, overall, the K4 likely offers the best tradeoff among all features among all suits so far in the K-series. In future iterations in the K-series, some work needs to be done to improve the reliability of the pocket seals. One potential solution is to increase the margin size of attachment, add hand stitching if needed, and then apply a generous amount of Aquaseal before any testing (Figure 6).

Figure 6: The K4 suit in action, the neutral buoyancy improves mass distribution, decreases straightening torque.

As a separate improvement, general protection can be increased by simply increasing the thickness of the two Chocobar plates in every pocket. That will keep the result neutrally buoyant, so it will offer the same advantages at no extra cost. While the overall mass would increase proportionally to thickness, neutral buoyancy means no extra ballast would be necessary. Because ergonomics of flexibility is based on the thickness of the neoprene at the joints, and the increased composite thickness does not affect that, it follows that the improved suit would be equally flexible for the diver, while offering more thermal protection. Further improvements can be implemented in the design and fabrication of the helmet. Instead of a hood upgraded with individual pockets, it should be possible to take advantage of the fixed rigid shape of the upper skull to allow the production of a customized rigid skullcap made of interlocking Chocobar plates or strips. Once completed, the skullcap can be attached to a commercial hood by the same method or sandwiched between two thin watertight hoods glued together. When properly padded with neoprene on the inside, the result should be comfortable, watertight, and very warm. Considering much heat is lost through the head, an efficacious helmet should be well worth the effort. Furthermore, the skullcap can be left with lowest line above the ear as is with the current design or extended below for extra protection. The latter option would require extending the mask strap as well as leaving a round area around the ears free of the composite but likely padded with thick neoprene, to combine protection with the ability to exchange air and prevent ear squeeze.

Diver A consistently reported some difficulty in donning the K4 suit. With all K-style suits, there is a decreased overall stretchiness of the sleeves, as large areas are covered with non-stretchy composite and reinforced with external pockets. On the other hand, some stretchiness is required to accommodate the body of the diver as well as provide a tight fit minimizing pockets where water might accumulate in a wetsuit. To ease the process with the K suits, a trick well known in the diving community was applied, involving smearing the body of the diver with shampoo before donning, to decrease friction with the material and help with the tight fit. Incidentally, the failure of the seam in Test #1 may very well be attributable to the extra stress on it during the donning process. A more sophisticated solution would be to introduce zippered folds on the forearms, upper arms, ankles, and thighs. To don, the zippers would be opened, to allow expansion of the neoprene folds, which would increase the diameter of the respective limb sleeves. After the diver is in, the folds would be folded in and zippered.

This would make donning and doffing much easier, at the expense of some more careful ergonomic tailoring of the undersuit. As final food for thought, we offer the hypothesis that the measured performance of the K suits is underreporting the thermal advantage, because that is assessed by comparison to significantly less ergonomic suits. The simple idea is that the diver must work significantly harder to swim in an 8 mm suit than a diver in a 3 mm suit. Hence, the former generates and dissipates more heat. As a result, the 8 mm diver must be warmer than he would be if he did not have to work so hard. Hence, ironically, the poor ergonomics may be improving the thermal performance, producing an unfair comparison in the field testing of the K-series. Perhaps a simultaneous study of the diver metabolism under a controlled and equal amount of useful mechanical work can shed some light on this and help more fairly compare the suits' performances in future studies.

CONCLUSION

The K4 diver suit is presented herein. Built by the Chocobar technique, the K4 is far easier to manufacture than its predecessors the K1 and the K2 suits. The field test results showed the K4 outperformed a standard 7/5 mm neoprene suit by +3°C at depth, as well as in flexibility, weight distribution, handling, and required ballast. The K4 is somewhat less thermally protective than the K3, but that tradeoff for neutral buoyancy is a significant gain. The K4 is overall the best suit in the series so far, offering a combination of advantages to commercial, recreational, and military divers.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare regarding this manuscript and the work it describes.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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