Cornell University Autonomous Underwater Vehicle Team

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Pollux UHPV

Technical Report

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Contents

1 Abstract

The upper hull pressure vessel (UHPV) houses custom printed circuit boards (PCBs), a computer, a camera, a number of sensors, and various SEACON underwater connectors. The UHPV allows for easy communication between the main circuit boards with the various thrusters, battery pods, and sensors in external enclosures while keeping the PCBs themselves in a safe, central, and easily accessible location. Pollux's UHPV aims to be an experimental step away from previous CUAUV UHPV designs, trading ease of manufacturability for a more efficient form factor better suited for the enclosures attached to Pollux. With a large top opening and easy to optimize rectangular dimensions, Pollux's UHPV will prove to be an adaptable and user-friendly UHPV for both the mechanical and electrical teams.

2 Design Requirements

2.1 Constraints

I must adhere to the following requirements throughout the design of this project:

- Must fit and protect the racks, forecam, and their components
- Will seal to an appropriate working depth for competition (30 feet minimum, 50 feet recommended)
- Must have a port for vacuum sealing
- Must securely mount to the frame
- Must be machinable
- Will accommodate bend radii of SEACON connectors

2.2 Objectives

I will accomplish these goals to the best of my ability throughout the design of this project:

- Minimize combined weight and displacement
- Minimize difficulty of unsealing the hull and accessing components
- Minimize difficulty for machining
- Provide clear view into the racks for debugging
- Be relatively even in balance

3 Previous Designs

3.1 Thor/Artemis (2016-17)

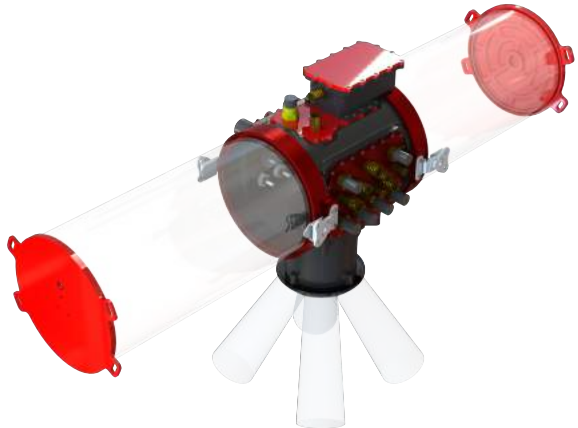


Figure 1: UHPV on Artemis.

Since 2014 all main subs have employed a dual-hull design around a central midcap. Creating a long profile for the subs, this design gives a large amount of room for mounting external enclosures and manipulators, while within the UHPV the two hulls allow for different areas to be designed around our custom boards and for COTS electrical components, and finally the midcaps (up until Artemis) have had the Doppler Velocity Logger (DVL) directly integrated into them. However, since Pollux will not have as many external enclosures as a main sub and lacks a DVL, adopting the dual-hulled design would make little sense.

The main design element from Thor and Artemis present on Pollux is the removable SEACON panel, since it will allow Pollux's UHPV to be updated for different connector requirements in future years.

3.2 Loki/Apollo (2016-17)

Figure 2: UHPV on Loki.

The short, large diameter monohull UHPV design of Loki and Apollo is the only mini sub UHPV design which CUAUV has previously used, since Hercules was never actually machined. This design included an in-hull forecam and downcam, as well as SEACON and Blue Robotics cable perpetrators screwing directly into the large forecap of the UHPV. While an effective design, this style of UHPV suffers from being very buoyant and when combined with the addition of so many external enclosures to Apollo (making it a relatively tall sub) caused serious control issues. As such, and in effort to try new and untested designs with future mini subs, Pollux's UHPV aims to step away from this past design in order to improve on its drawbacks while testing different approaches to elements which Loki's UHPV succeeded in.

3.3 External Influences (2017)

(a) Caltech's Dory

(b) S.O.N.I.A.

(c) SDSU's Perserverence

Figure 3: External UHPV design influences.

Although Pollux's UHPV draws from past CUAUV designs and philosophy, a decent amount of design inspiration came from observing other team's non-cylindrical monohull UHPV designs at Robosub 2017. Among those observed, three of them were influential on the initial design brainstorming for Pollux's UHPV: Caltech, S.O.N.I.A., and SDSU. Since S.O.N.I.A. and Caltech's designs relied on manufacturing resources CUAUV lacks or techniques deemed too experimental for this year (like 5-axis CNC or carbon fiber work), SDSU's Perseverance ended up being the primary external influence on the UHPV's design. With a similar boxy configuration which "enables users to have maximum access to internal components without the impedance of tubular cramped spaces or multiple separate enclosures" (SDSU 2017 Journal Paper, Section III.A.1.) and single seal over the entire top of the enclosure, the accessibility and space efficiency goals of their design are similar to those for Pollux's UHPV

4 High Level Description

Figure 4: An exploded view Pollux's UHPV's high-level components.

Pollux's UHPV design represents a step away from previous CUAUV UHPV designs in order to embrace a philosophy of trying experimental designs with our mini subs while continuing with more conservative designs on the main sub. The major change in geometry (from a cylindrical acrylic hull to a rectangular aluminum hull) is driven by attempting to hold the mini sub's overall size roughly constant while simultaneously increasing the number of components on and inside of it to be on par with our main sub. By adopting a rectangular form factor, the geometric constraints within the UHPV are more relaxed, allowing for more efficient use of the internal space and a reduction in the amount of empty within Pollux. Although the UHPV will ultimately weigh more than Loki/Apollo's, its lower displacement will counteract the additional weight and reduce the required final weight for Pollux to be neutrally buoyant. Additionally, most of the non-hull components will be manufactured at a CNC company, DATRON, in order to mitigate some of the risk in manufacturing features which have not been previously attempted.

Pollux's UHPV is made up of three primary components: an aluminum hull, a lid, and a removable SEACON panel. The main seal for Pollux is a square #279 o-ring double bore seal between the hull and lid, and it is held on by four draw latches (McMaster 1794A55).

4.1 Hull

Figure 5: Pollux's UHPV's hull. Opening on the right for the forecam, holes along the side for mounting draw latches and to the frame.

Figure 6: The back of the hull.

The backside of Pollux's UHPV is dominated by two large cutouts for the SEACON panel. Though the panel is sealed on using a single #262S o-ring (along the entire outside of the panel), the cutout for the connectors is split into two halves since the size of the panel/cutout would cause unallowable stresses and displacements if left unsupported. In order to fix this, a center support pillar was added with holes for the SEACON panel to mount to from the inside for support, as well as a clearance cutout for the ball valve's threads, and holes to mount a splash plate.

(a) Detail of the support pillar and splash plate.

(b) The inside of hull.

The inside of the hull does not include many features besides 4-40 mounting holes for the racks and a $\frac{1}{4}$" NPT tapped hole in a corner for the depth sensor. Although they will increase the difficulty associated with machining this part, the $\frac{1}{2}$" radius fillets at the bottom edge on the inside proved necessary as the stress concentration created by having a sharp corner there pushed stresses far outside of our allowed factor of safety.

Figure 8: Detail of the bottom and side weight reduction on the hull.

The bottom face and sides of the hull feature large amounts of weight reduction, because the size of the UHPV necessitates having high thickness areas in order to combat the effects of pressure at depth on the large faces, but do not require these higher thicknesses in a uniform manner. While on other pieces (such as Castor's UHPV's aft endcap) such weight reductions are placed on the inside face of the part, this pattern will be machined on the outside as the hull is too deep for most tooling to reach the bottom. Additionally, having it on the inside would add to the UHPV's displacement while the outside does not. The weight reduction around the sides of the hull is designed so that it can all be machined in the same CNC setup as the bottom's weight reduction by running a 1" ballmill around the outside edges.

4.1.1 Machining

Machining the hull could possibly overtake Thor's Midcap as CUAUV's toughest machining projects to date, and care has been put into the design in order to try and minimize the risks presented during its machining process. The features of the hull will require a minimum of 4 setups on the CNC (top, bottom, front, and back), but the length of some of these operations (especially clearing out material on the inside) may require multiple setups based on CNC based on what time slots are available. Because of this, and because the part is likely to deform while it is machined (due to the volume of material being removed), features will be machined with extra material left on at first so that the final dimensions will be accurate (or at least functional). This is especially important for the sealing surface for the square bore seal since it is probably the most failure-prone feature from a machining point of view.

4.2 Lid

Figure 9: The lid to Pollux's UHPV.

The lid on Pollux's UHPV aims to combine accessibility and visibility for all of the components housed within the UHPV. In order to accomplish this, the lid is made of two main parts: an aluminum collar which acts as the main sealing interface with the hull, and a large acrylic window which is sealed onto the collar with a #278S o-ring. The collar provides the structural strength and rigidity for the lid while the window allows for relatively unobstructed visibility into the hull. In order to distribute the load of the sealing bolts on the window, a rubber gasket and aluminum flange have been included on top of the acrylic of the window. The lid is held on the hull by four draw latches, though under normal operation the latches are not putting any stress onto the lid. In anticipation of difficulties unsealing the main seal, small cutouts have been included around the outside edge so there will be somewhere to wedge a tool in order to pry the lid off.

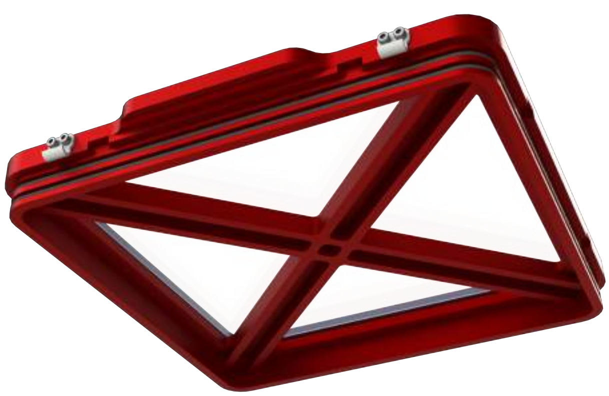


Figure 10: The underside of the lid.

The cross shaped beams across the lid have to be relatively thick in order to support the window against the external pressure from the water, so they have been designed to effectively be two crossed channels of aluminum to balance strength and weight. All of the weight reductions are designed to be uniform in depth, besides in the corners where that depth would conflict with one of the tapped holes for the window's seal on the other side.

4.2.1 Machining

Accurately hitting the dimensions for the o-ring grooves will pose a large challenge in terms of machinability for the lid. However, the geometry of the parts allow for all of the machining (besides the tapped holes to mount the latches) to be done at DATRON over winter break, so it will be easier to hit the tolerances required. In case the main seal proves to be unmachinable as-is, there will be a contingency plan to replace it with a less user-friendly but more easily machinable version (which would seal separately and be epoxied onto the location of the existing seal).

4.3 SEACON Panel

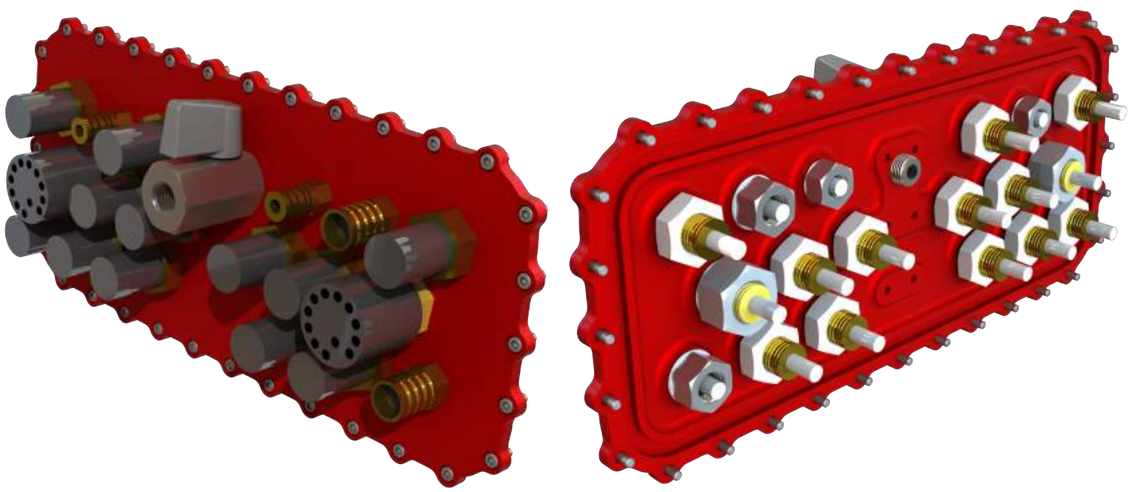


Figure 11: Pollux SEACON Panel.

Pollux's SEACON panel is densely packed in order to fit all required SEACON connectors onto a panel on only one side of the hull, which it seals to with a #262S o-ring face seal. Although there is clearance for actually populating the panel, connectors towards the middle and bottom will be harder to access. To mitigate this issue, connectors which are rarely removed (thrusters, battery pods, etc.) have been placed in harder to reach spots while frequently accessed connectors like tether occupy spaces along the top row. There are no SEACON along the center of the panel because of the support pillar on the hull behind that part, which screws into the panel from the inside and provides the support against deflection that this otherwise too large SEACON panel requires. Pollux's ball valve for vacuuming/unsealing the UHPV is located at the top center of the panel because this location allowed for the addition of holes to the UHPV to mount the splash plate.

4.4 Mounting to Vehicle

Figure 12: The UHPV's attachment point to the frame.

The UHPV mounts to the frame through six $\frac{1}{4}$"-20 tapped holes on bosses on either side of the hull. Although the top plate of the frame lies directly below the UHPV, it does not contact or support the UHPV.

5 Manufacturing

5.1 SEACON Panel & Lid

The majority of manufacturing for these pieces was done in December at DATRON Dynamics which meant that going into our formal manufacturing period the parts were almost complete with very tight tolerances (with the exception of certain features like the SEACON ports or the lid's main seal o-ring grooves). The finishing operations went well, with the SEACON panel requiring a shift and a half to be fixtured to another plate and all the SEACON ports added, and the lid requiring a CNC setup (as well as becoming familiar with running keyseat cutters on the new Haas machines). Although a small mistake in z-axis zeroing caused the lower groove to have a set in one of its walls, the parts came out fine with minimal difficulty.

5.2 Hull (CNC operations)

While the manufacturing for the other components went well and the end result for the UHPV turned out fine, the hull proved to be a much more difficult (or 'horrifying' according to Laura) and time consuming task than anticipated. The long length of cut (LOC) required for the inside and outside of the hull meant that traditional higher speed machining techniques were not viable, and even increasing depth of cut and stepover with lower feedrates to keep the tools at max deformation had minimal results.

Additionally, though the hull was designed to have had its external weight reduction machined in a single setup from the bottom, it ended up being switched to 4 separate setups around the outside so that shorter tooling could be used. Had that been the plan from the beginning then the weight reduction would probably had a different pattern which would have made fixturing for later operations easier. For example, it would have left a solid strip of aluminum along the bottom edge of the port and starboard sides so that we wouldn't have needed to mount strips of aluminum to the frame mounting holes in order to grip the hull in the vise to remove the inside. Additionally, when projects of this scale are placed on end in the Haas, tool height/probe clearance starts to become an issue, since the hull was within an inch of hitting the probe in the tool changer.

A few details, such as the final filleting of the bottom of the inside with a ballmill, were omitted since the impact on the final design was was not worth it compared to the risk of running another new tool at that point in the operations. Running the main sealing surface as a final operation may not have been necessary, but it did result in the surface being within tolerance and sealing without difficulty.

The transition to Fusion 360 from ProToolmaker for CAM meant that some degree of toolpath customization was lost, both from unfamilarity with the new program and Fusion 360 lacking features which ProToolmaker had. The steps on the outer corners of the hull are one such result of this, though they have no functional impact on the deisgn. Finally, the shear volume of material being removed put stress on the machine's chip removal system, and the operations had to be occasionally paused in order to blow out the chips from inside the hull, especially in the back right corner since the flood coolant could not reach the tool in that area.

5.3 Hull (manual operations)

For the most part the manual operations on the hull just translated to adding a large number of 0.28" depth, 4-40 tapped holes all over the front, back, and inside of the hull. These setups went relatively well, and though two #43 drill bits ended up breaking in the SEACON panel's mounting holes, the panel was designed with a number of sealing screws and has demonstrated no issues despite the missing screws. The initial plan was to add all external holes before removing the inside material, but due to running out of our #43 drill bits after the two mentioned above broke, the fore camera's mounting holes were left until after the inside was removed and new bits could be ordered. I strongly do not recommend doing this in the future and just using the shops non-carbide #43 drill bits because the fixturing required for the hull after the inside is removed to mitigate chatter is terrifying (see below). The holes on the inside bottom of the UHPV ended up being fine to machine

Figure 13: Fixturing the hull to add the fore camera's mounting holes.

with a certain level of patience. Since all were so far into the hull, specialized tooling was required to reach them in the form of a reach $\frac{1}{4}$" NPT tap, 6" long #2 center drill, and a 6" long #43 drill bit. Since all the holes were at minimum the small size tap handle tool's radius away from a wall, tapping them was no issue. The total number of extra mounting holes in the bottom was reduced from the initial (somewhat over-zealous) amount in interest of time, but the number left should be enough for future racks to utilize them for mounting in different configurations.

5.4 Integration

The process of finally integrating the UHPV and its components went well. Though dense, the SEACON panel was not difficult to populate as long as the order connectors were added had some forethought put into it. Additionally, the lid has proved to be much easier to seal/unseal from the hull than we'd expected, meaning that the cutouts for prying it off will likely go unused. While the lid is easy to get into the hull, the hull is not easy to get into the frame, and required percussive persuasion to get it into place after the frame had been assembled. The only 'major' issue which arose during integration was the fact the depth sensor stuck out the bottom of the UHPV into part of the frame due to a miscommunication when that piece's weight reductions had been done, but this was solved by putting the frame piece back on the mill and removing the offending strut.

6 Modifications

A number modifications were made to the UHPV over the course of manufacturing and assembly, but none have substantial impact on the design:

- External weight reduction was switched to being 4 setups instead of 1
- HUMG12 flex SEACON switched to a HUMG5 because we did not realize that HUMG12 was not an available connector after the electrical subteam requested it
- Threads for the ball valve had to be cut down because the clearance hole behind it is slightly too small for its threads
- Splash plate is not necessary because ball valve vents onto a solid plate since I forgot to put the central hole in it
- O-Ring for the SEACON panel downsized to a 261S (from 262S) because I botched the dimensions for its groove by taking its ID instead of A dimension
- O-Ring for the window is (currently) a round o-ring on a face seal because square o-rings of that size have to be ordered custom which is expensive
- O-Ring for the main seal was downsized by 1 size (to 278 from 279) so that they are tighter in the groove despite proper dimensioning for 279. This change may make sense to be standard procedure for future non-circular bore seals (or possibly designing halfway between sizes, it passed leak tests with both)
- A 1.5mm thick acrylic insulating layer was added at the bottom of the hull to mitigate risk of boards scratching the anodized layer on the hull and shorting through it
- The 6 extra bolts for the SEACON panel from the inside of the UHPV are unused because the panel seals onto the hull without them

7 Current Status

Pollux's UHPV has been fully manufactured, anodized, integrated, leak tested, and in-watered, meaning that it is complete for this year. The racks inside of it are still in the process of being integrated, but no changes to the UHPV are expected during that process.

8 Future Improvements

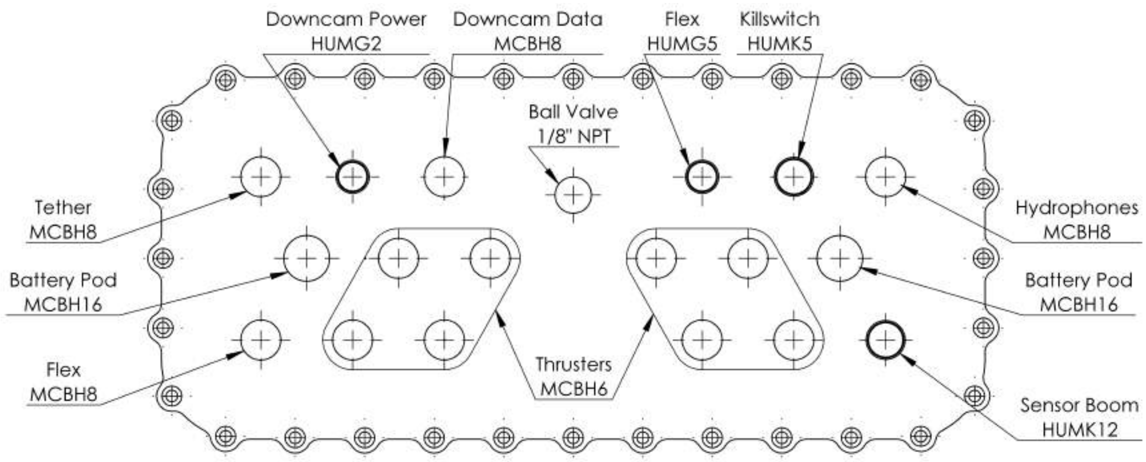
There are a number of directions in which the UHPV design can be improved, mainly in relation to how it interfaces with other projects and components, though other improvements may be required in response to difficulties which may arise during the manufacturing and testing process. The internal space within the UHPV can probably house more electrical components than it is this year, but designing racks to efficiently fill the space while simultaneously being appropriately sized for use within Castor's UHPV is understandably difficult. Next year, having the constraints pre-set may allow for improvements in how the space is utilized. Additionally, the solid aluminum body of Pollux's hull may allow for heat sinking directly into the body of the UHPV as opposed to the use of bulky COTS heatsinks, which could further reduction in weight.

Future iterations of similar rectangular UHPV designs should probably opt for two SEACON panels on either side of the UHPV (as opposed to the single one in the rear which was implemented here to reduce machining setups, but ultimately did not since the sides were all done as separate setups) because the geometry of the UHPV makes the space directly behind it valuable real estate for components on the frame. Finally, as the two vehicles are approaching each other in UHPV size this year, it should probably be noted that Pollux's UHPV includes space and connectors for all components which are utilized on Castor, meaning that it could hypothetically become a main sub UHPV for future years if we decided to scale back the components on the mini sub and in effort to make it smaller and actually 'mini'.

After having gone through the process of manufacturing the UHPV, reducing the length of tools required to manufacture it is something which would be good to design towards for future UHPVs. In terms of redesigning this UHPV, that would likely mean making it a clamshell design with the main bore seal halfway down the sides instead of the hull and lid configuration which Pollux will have. Such a design would require multiple SEACON panels and might not facilitate an internal forecam (or at least not as easily as this design does), but such changes would be worth it by saving a lot of headache at the manufacturing stage.

Appendices

A SEACON Panel Layout



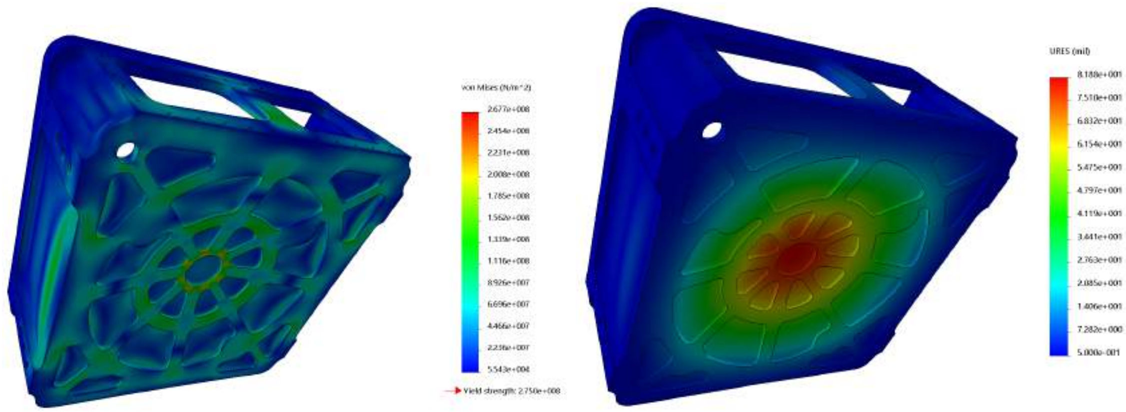
B Purchased Components

Component
MSI US300 Depth Sensor
$\frac{1}{8}$" NPT Ball Valve
4x Corrosion-Resistant Draw Latches

C Finite Element Analysis

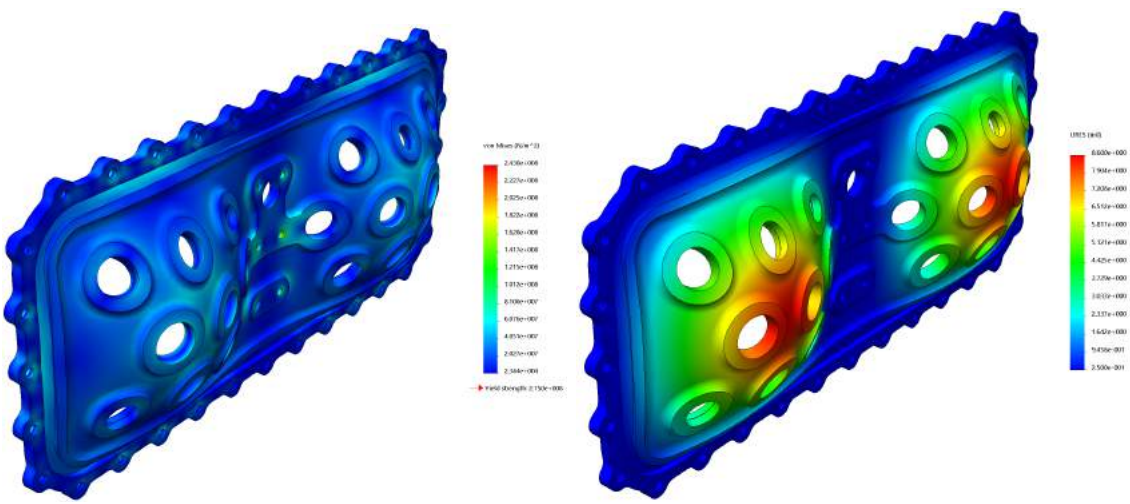
The following are the results from SolidWorks Simulation after applying a 250kPa hydrostatic pressure load meant to simulate Pollux operating at our rated depth of 20 meters with a partial vacuum pulled inside of the UHPV. Although ANSYS is usually employed for our FEA, the highly iterative nature of weight reductions and the thickness of parts on Pollux's UHPV lead me to favor SolidWorks Simulation since the iterative process of changing a dimension and then checking FEA results is significantly faster within SolidWorks versus jumping back and forth between programs.

Part	Max Stress (MPa)	Max Deformation (0.001")	Factor of Safety
Hull	267	81.8	1.03
SEACON Panel	243	8.60	1.13



(a) Equivalent Vin-Mises Stress (b) Total Deformation

Figure 1: Hull SolidWorks Simulation Results (250kPa Pressure Load)

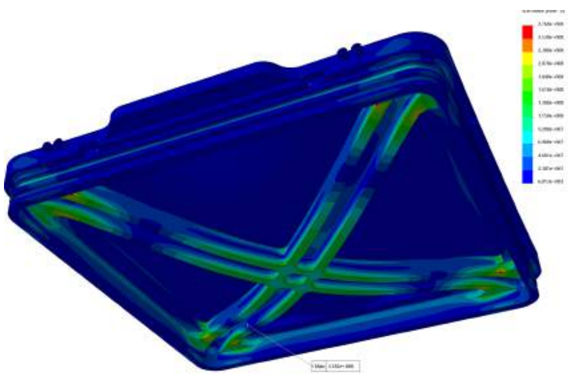


(a) Equivalent Vin-Mises Stress (b) Total Deformation

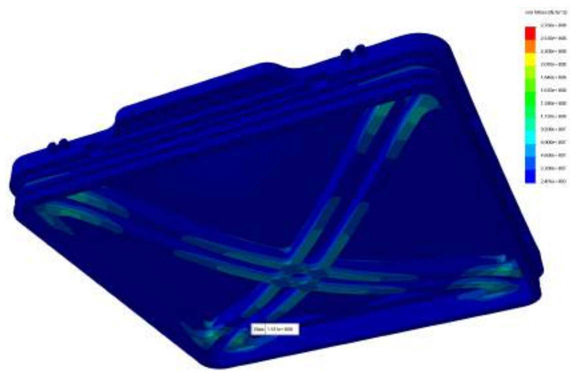
Figure 2: SEACON Panel SolidWorks Simulation Results (250kPa Pressure Load)

The large size of the lid for Pollux's UHPV combined with the design constraint of it being a large clear window means that having a design which passes our standard 250kPa hydrostatic load test would not be viable for use due to weight and bulkiness. As such, the lid of the UHPV does not, as designed, pass this test due to stress concentrations in fillets near the corners of the lid. However, under a more realistic 100kPa hydrostatic load (roughly equivalent to 1.3x the normal operating pressure for our submarines in testing and at Robosub), the stress falls to allowable levels, so for the sake of experimenting this design Pollux has a lower effective depth rating than the 20 meter standard for CUAUV designs.

	250kPa Load	100kPa Load
Aluminum Max Stress (MPa)	378	151
Aluminum Factor of Safety	0.73	1.82
Acrylic Max Stress (MPa)	30.0	15.0
Acrylic Factor of Safety	2.87	5.73
Max Deformation (0.001”)	82.8	33.1

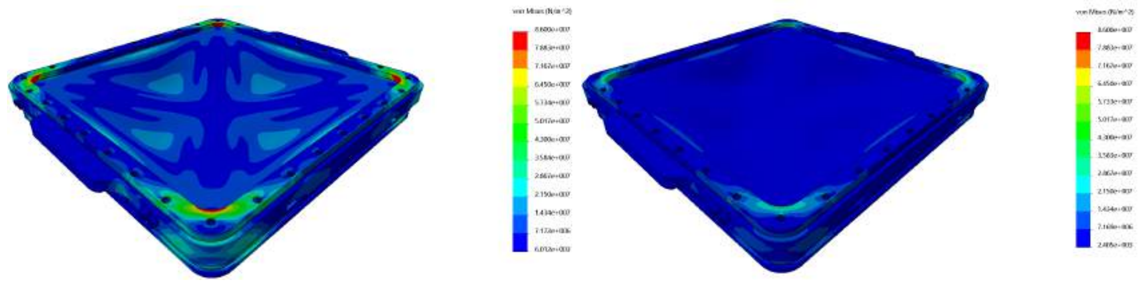


(a) 250kPa Load



(b) 100kPa Load

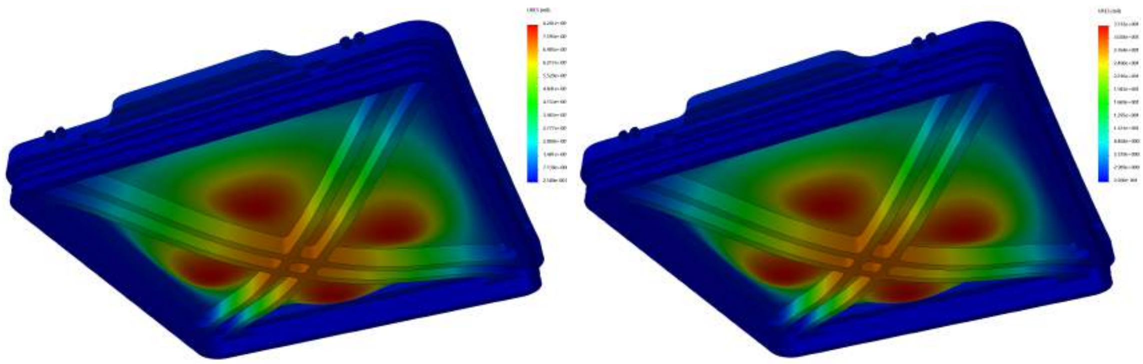
Figure 3: SolidWorks Simulation Results for Stress in Aluminum Sections of the Lid



(a) 250kPa Load

(b) 100kPa Load

Figure 4: SolidWorks Simulation Results for Stress in Acrylic Sections of the Lid



(a) 250kPa Load

(b) 100kPa Load

Figure 5: SolidWorks Simulation Results for Total Deformation of the Lid