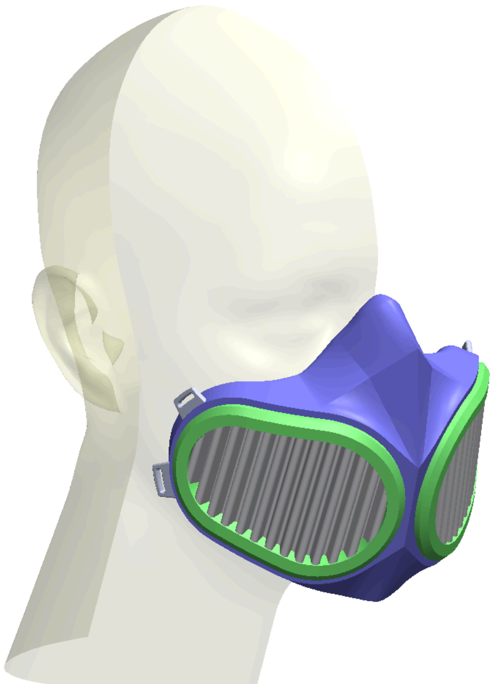
Open Aeros Respirator Prototyping Process



Prototyping Goal

The goal of this prototyping process development is to create a process by which anyone with a limited set of widely available tools can rapidly iterate an elastomeric respirator design. We use a combination of room temperature Liquid Silicone Rubber (LSR) injection molding and 3D printed molds to achieve this result.

Respirator Design Process

Tools Used

- 3D Scanning: Artec Space Spider & Atrec Studio 17
- Solid Modeling: Solidworks 2022
- Slicing for 3D Printing: Bambu Studio & Prusa Slicer

3D Scanning

Desired real world features or geometry can be 3D scanned to incorporate them as reference in the solid model of the respirator/product to be created. For example an human face could be scanned and used as reference for the facial interface surfaces.

Mesh Import

Reference scanned meshes were imported into solidworks. Meshes were converted to a mesh solid. Solid body was oriented to align with symmetry to the default datums and aligned to a representative facial surface. Solid body was cut in half along right plane to allow for left right mirroring

Respirator Solid Modeling

It should be noted that consideration for high volume manufacturing was not given close scrutiny in the following design. This design was meant to aid in the rapid prototyping process design.

Filters

Filters were designed first and oriented against a representative facial surface. The filter media consists of two outer layers of protective spun bond material and an inner layer of melt blown filter media with an outer perimeter of silicone. Pleating was used to increase filter area and reduce pressure drop.

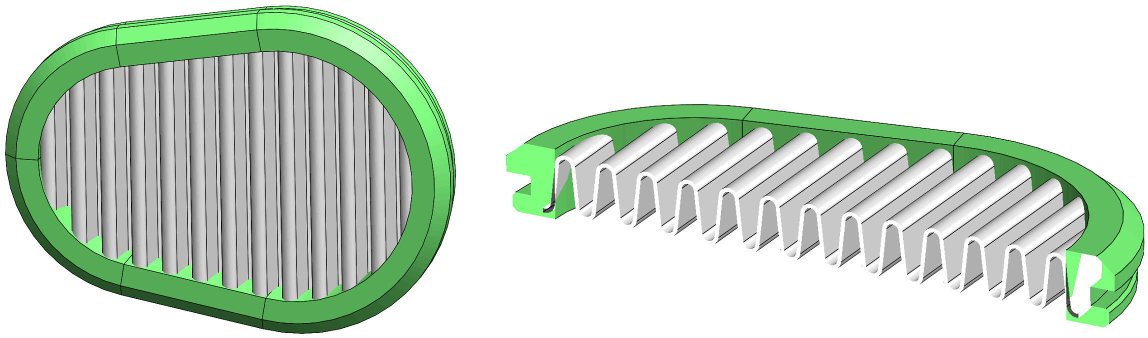


Fig: Removable Pleated Filters

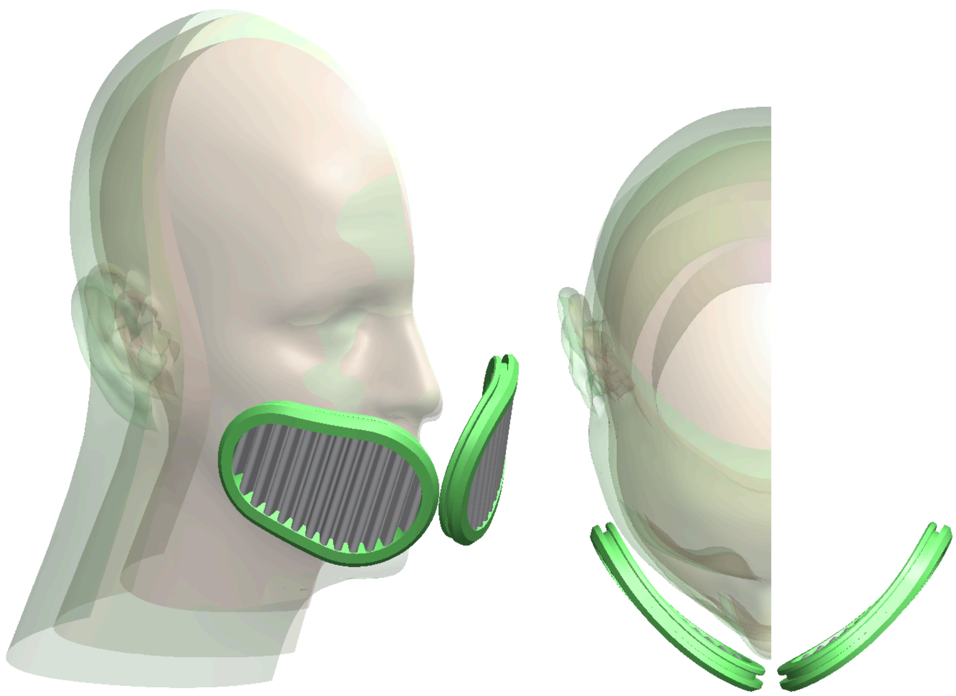


Fig. Filters Oriented Along Side Reference Face

Respirator Body

The respirator was then constructed beginning at the filters and working inward to the facial interface. The respirator part was modeled using many in context references in an assembly with the filter and reference headform parts. Outside surfaces were first constructed then inner surfaces were offset and a solid model created. Additional detail is provided in the following sections.

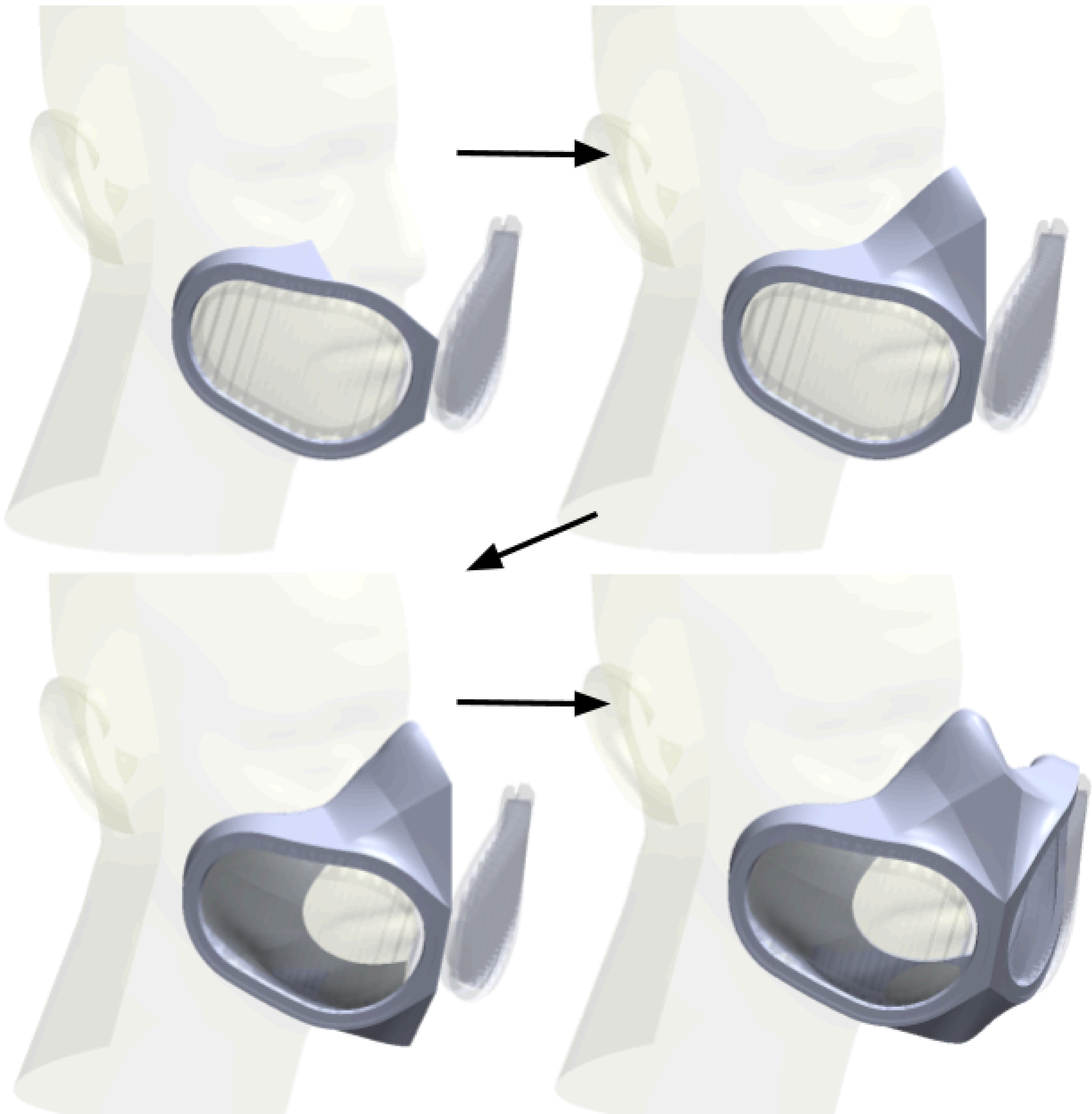


Fig: Respirator Body Design Progression

Respirator Body - Filter Surfaces

- Filter surface was copied and thickened to make a solid
- Ruled surfaces were extended towards the facial interface
- 3D Sketches of facial contours are used to trim the ruled surfaces

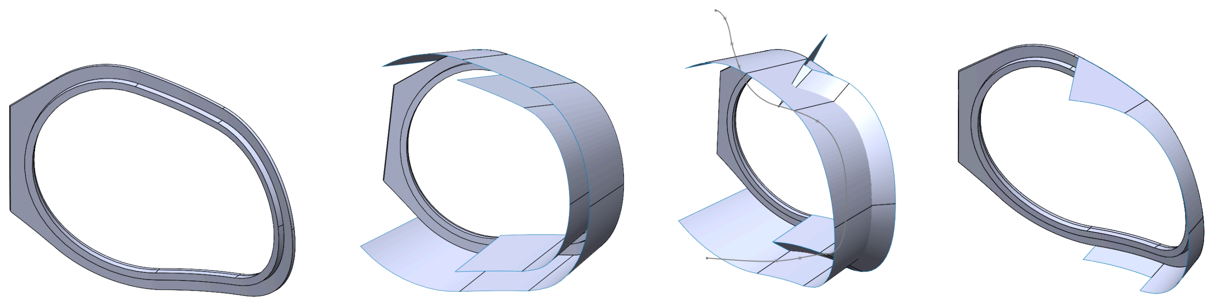


Fig: Filter Surfaces

Respirator Body - Nose & Chin Surfaces

- 3D Sketch was created to detail the nose and chin profiles
- Boundary surfaces were created from sketch
- Ensure each surface has 4 sides for more robust surface bodies

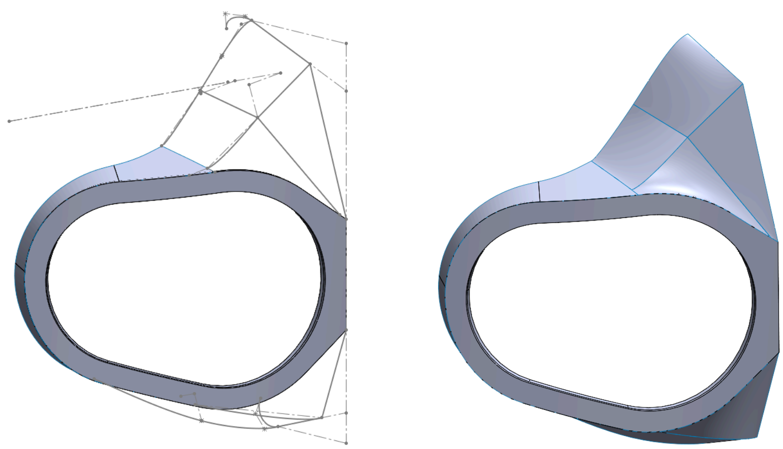


Fig: Nose & Chin Surfaces

Respirator Body - Facial Interface Surfaces

- 3D sketches of facial interface profiles were created using headforms
- Boundary surfaces were created from sketches
- Surfaces were mirrored to complete exterior of respirator body
- Inner surfaces were offset from outer and a bounder surfaces to join them into a solid

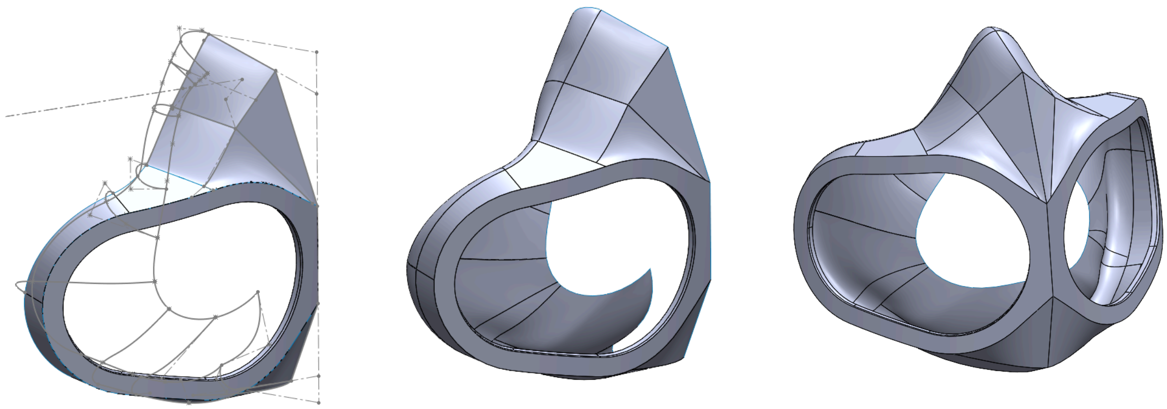


Fig: Facial Interface Surfaces

Strap Support

Respirator body stiffener and strap attachment were then added to the main body. An external and internal co-molded version have been created.

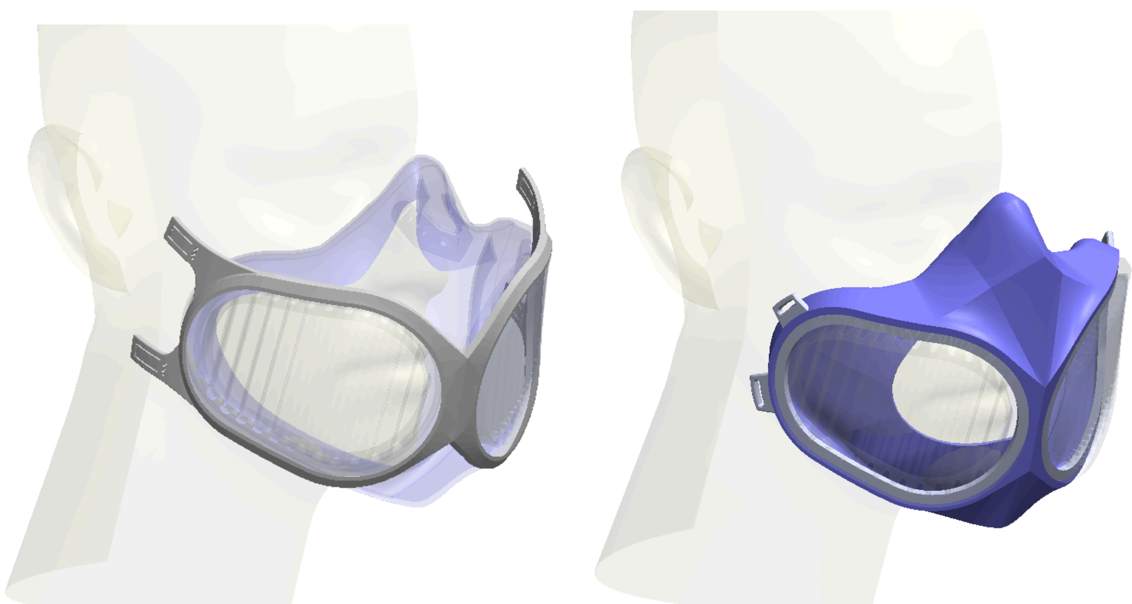


Fig: Respirator Body Stiffener and Mask Attachment, External & Internal Co-Molded

Nose Bridge Stiffener

An internal nose bridge stiffener was also added. A sketch of the general shape was projected onto the inside surfaces of the respirator body. The projected surface was offset and a boundary surface was generated to create a solid. A copy of the outer surfaces of the stiffener were thickened and merged with the respirator body to create the insert housing.

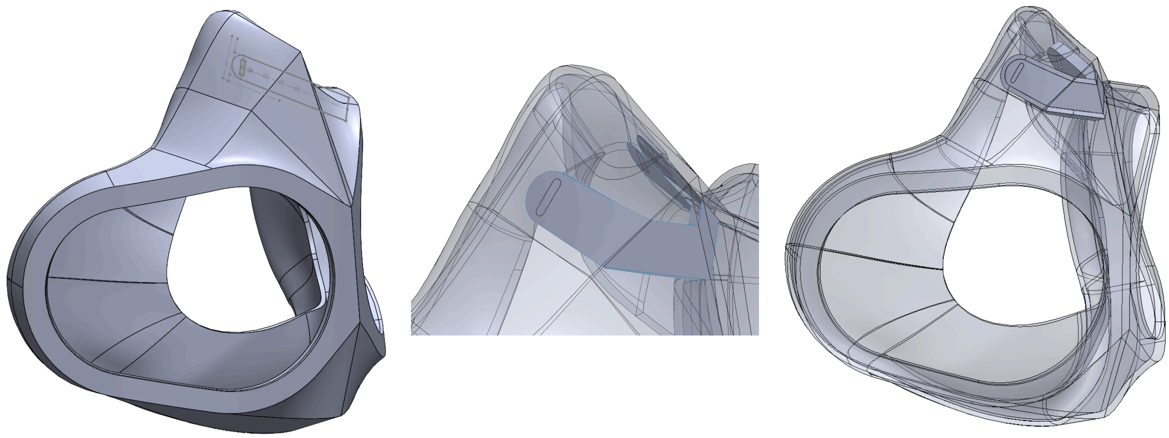


Fig: PCL Nose Bridge Construction

This stiffener can be printed out of PCL to provide a method of adjusting the fit of the mask. PCL can be permanently plastically deformed at a low temperature. The stiffener can either be printed separately and inserted into the finished respirator body or printed directly into the mold during its creation.

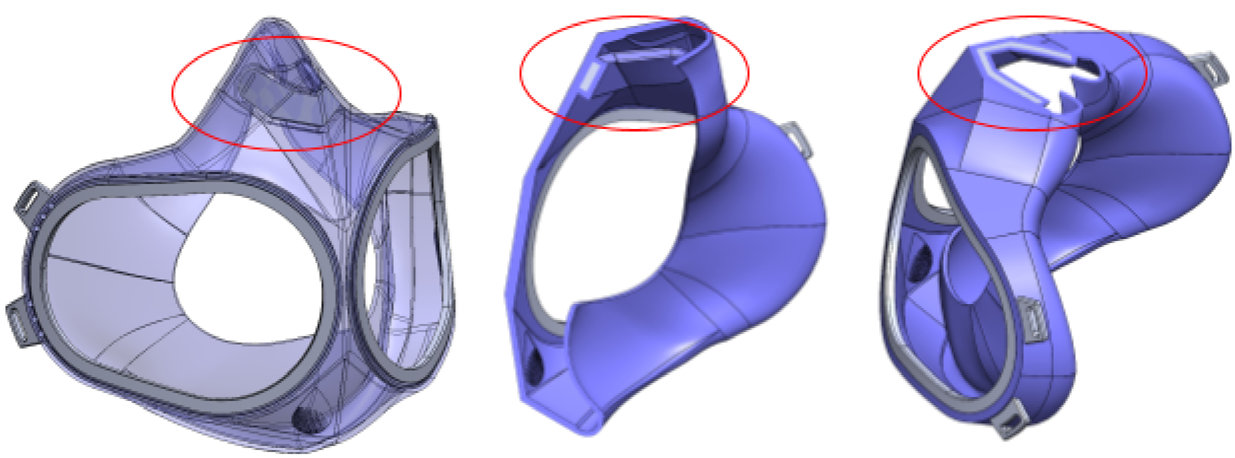


Fig: PCL Nose Bridge Stiffener

Design Iterations

A number of design iterations were rapidly created in solid works.

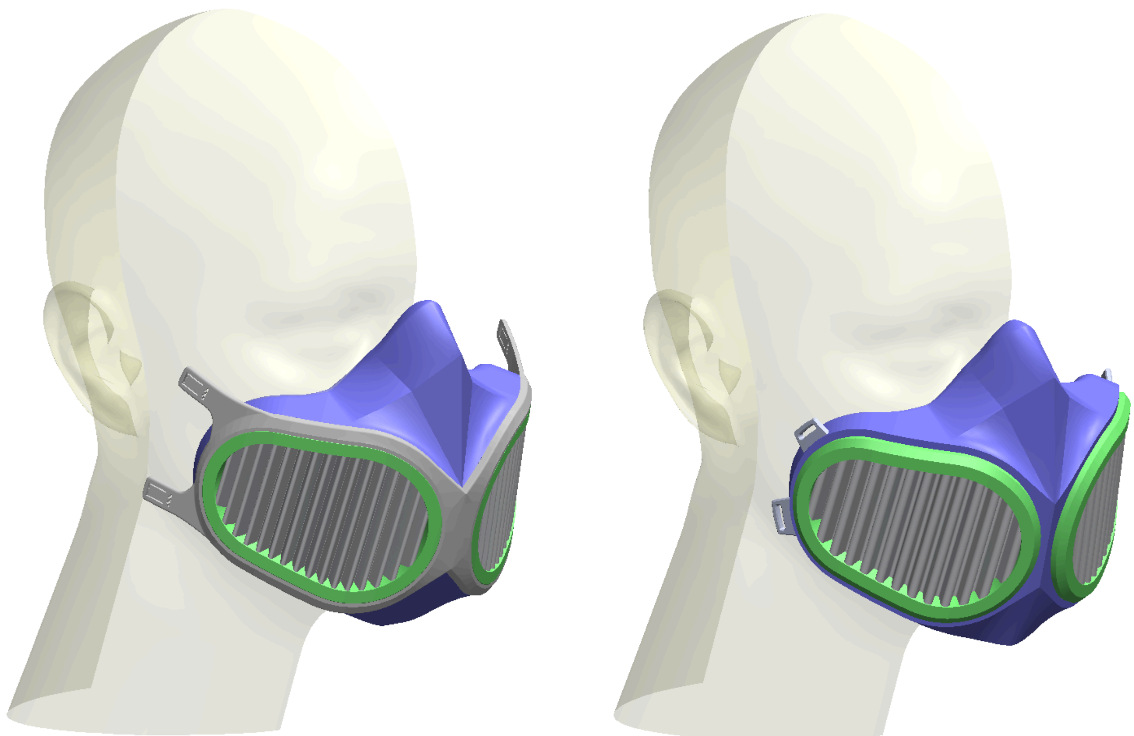


Fig: Completed Respirator Designs, External & Internal Stiffener/Strap Attachment

Surface Modeling Lessons Learned

We used Solidworks 2022 for the design of the respirator. Surface features were used extensively. During the development process a number of takeaways were gathered for working with Solidworks Surfaces in Solidworks 2022. We have included a list of them here for reference.

- When working with complex surfaces in Solidworks 2022 it is important to fully rebuild(*ctrl-q*) a part often to make sure references are not being lost or corrupted.
- If your surface geometry is based off of the geometry of an externally referenced part, routinely test your features by making slight changes to the externally referenced part to ensure your feature references are robust.
- In one particular case, when rebuilding a ruled surface, after a dimensional change to a parent feature(an offset surface body), the Feature IDs for certain reference inputs were lost. This resulted in the need to remap edges of the offset surface body in the ruled surface feature. The problem was solved by turning the offset surface body into a solid body prior to creating the ruled surface.

Thickness Analysis

Solidworks thickness analysis software can be used to identify any areas that are less than your desired or minimum thickness. Correct any thin areas in CAD. Results pictured below:

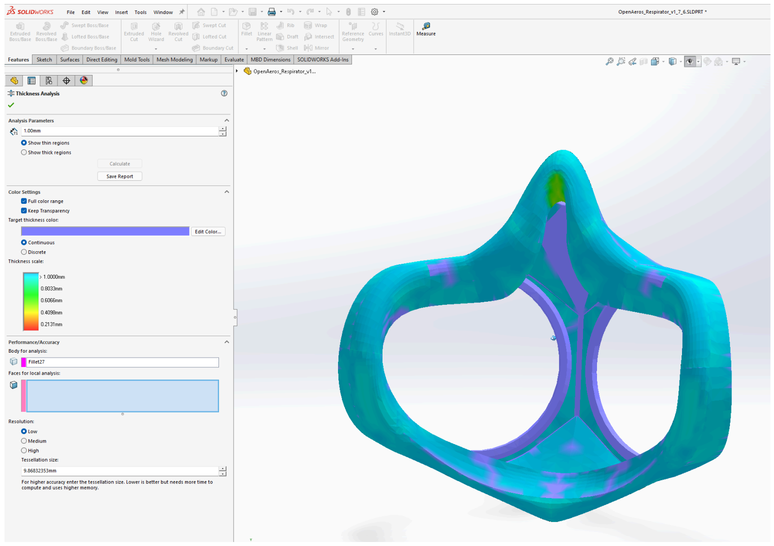


Fig: Thickness Analysis

Respirator Body Mold Creation

Mold Type

The respirator body will be cast from a platinum cured silicone for skin contact safety. We will be creating the respirator body mold using a novel method of mold manufacturing. The mold will be 3D printed as a single piece from a water soluble material, BVOH (Butenediol vinyl alcohol copolymer).

Mold Body Design

The part to be molded is inserted into a new solidworks part file that will become the mold. It is oriented so that during the printing process the number of horizontal surfaces is minimized to reduce the need for supports and allow for better surface resolution using the z-axis of the printer.

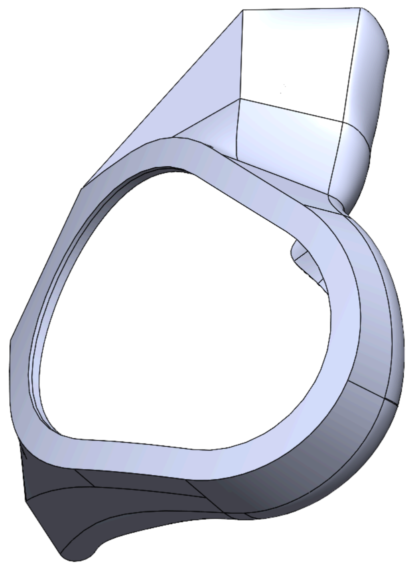


Fig: Orientation of Mask Body for Optimal 3D Printing

After the part is roughly oriented a silhouette sketch can be created parallel to the print surface. A surface body is created from the silhouette and then a second surface is offset from the first. The offset distance should be a multiple of perimeter extrusion width equivalent to the number of extrusion perimeters being used. This ensures that the inner mold cavity walls come into contact with the outside walls of the mold increasing mold strength.

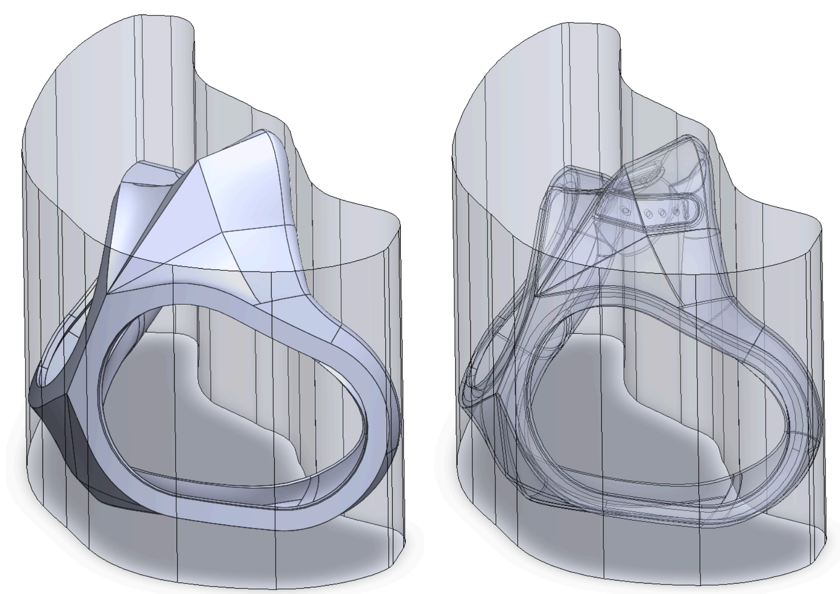


Fig: Mold Body Before and After Boolean Subtraction of Mask Body

To fine tune the orientation of the part and verify overhanging areas a slicer can be used. Keep in mind that when the object is turned into a mold the opposite side of the part will need support as we are dealing with the object's negative space which we will see more clearing after slicing the mold.

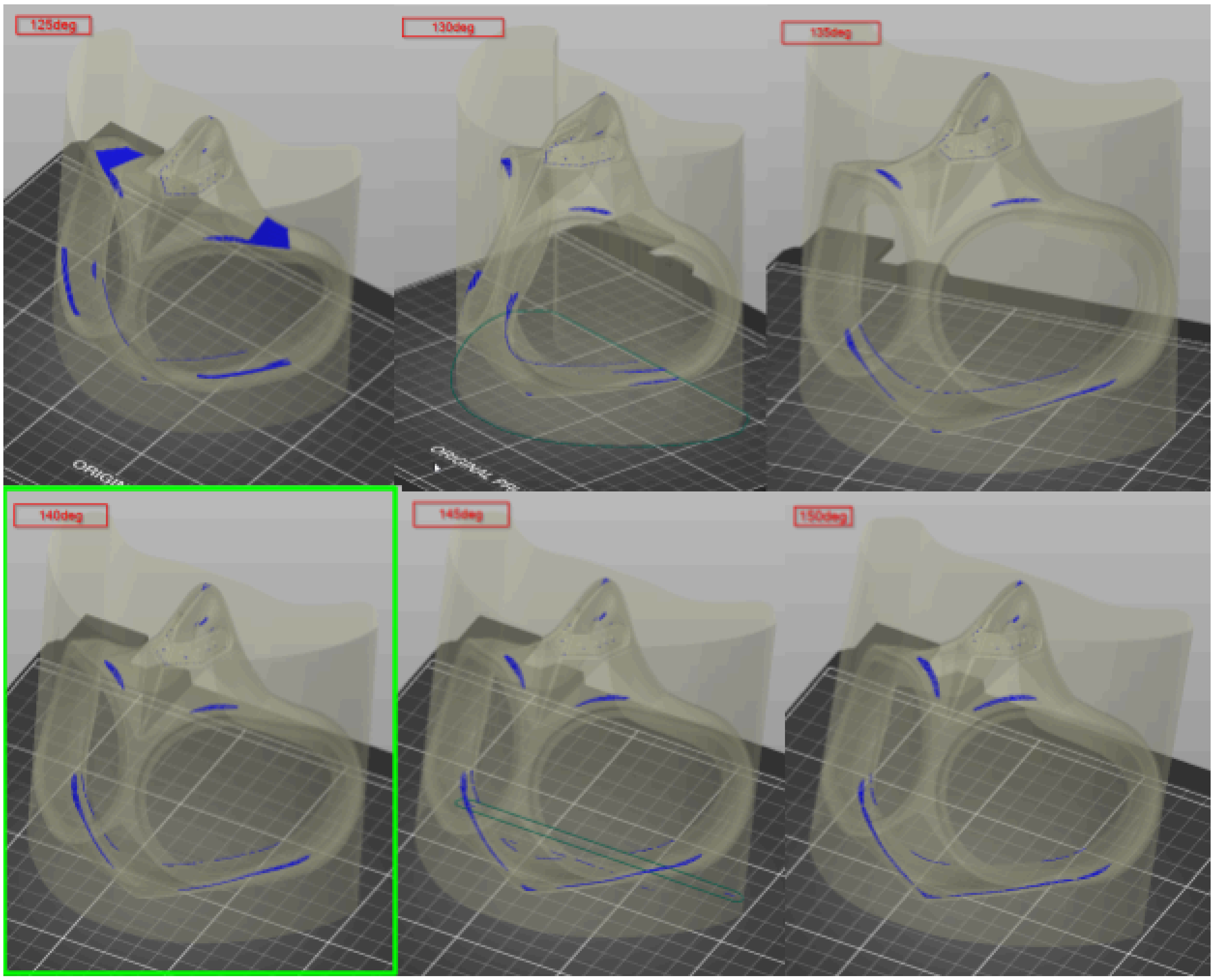


Fig: Mold Model Shown in Slicer at a Variety of Angles with Overhangs Highlighted, Green Highlight Shows Optimal Angle to Minimize Overhangs

Mold Cavity Manual Support Additions

The mold cavity can now be inspected for islands or large overhangs by cross sectioning parallel to the mold base. Islands are sections of the mold cavity that would be printed into thin air. Supports can be added as needed by cutting holes in the positive part prior to boolean subtraction or extruding support in the negative space afterwards. We opted for the former as it is simpler to model in solidworks.

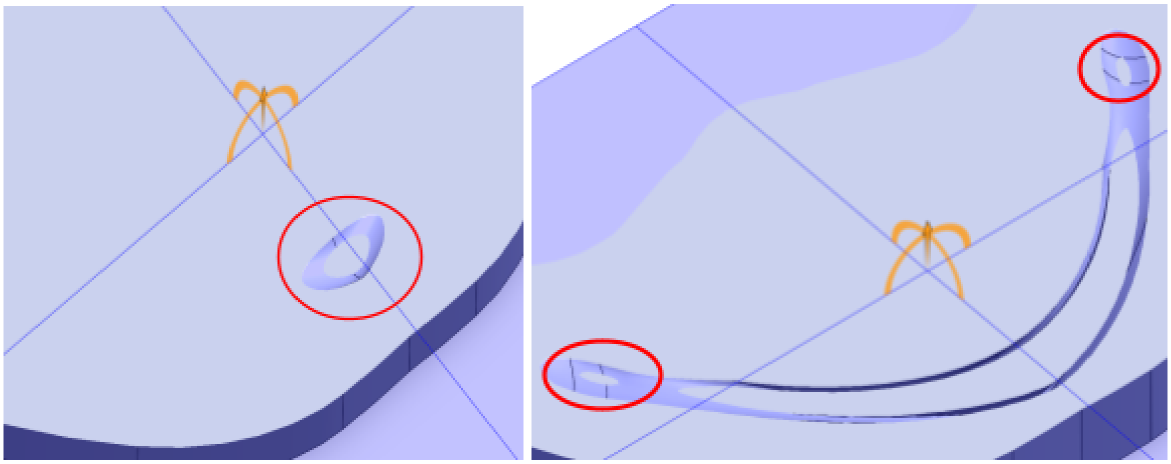


Fig: Cross Section of Mold body with Islands That Need Support When Mold is 3D Printed

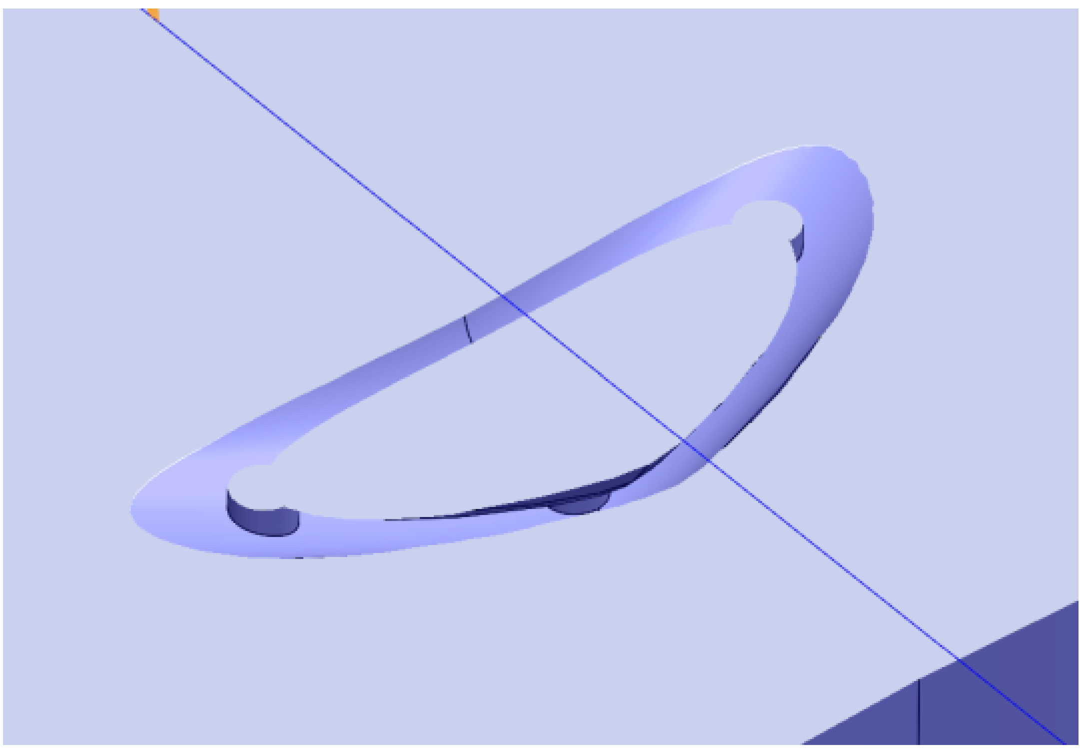


Fig: Cross Section of Mold Body with Closeup of Supported Island

Shot Port Considerations

A port for shooting the mold must be added to allow liquid silicone rubber (LSR) to flow into the mold. The orientation of the mold when printed does not have to be the same as the orientation during shooting. The mold pictured here is shot at 90 degrees to the print orientation.

Considerations should be made so the mold has a stable base during shooting. A fill port to accommodate the LSR dispenser's mixing nozzle can be added to the highest point of the cavity.

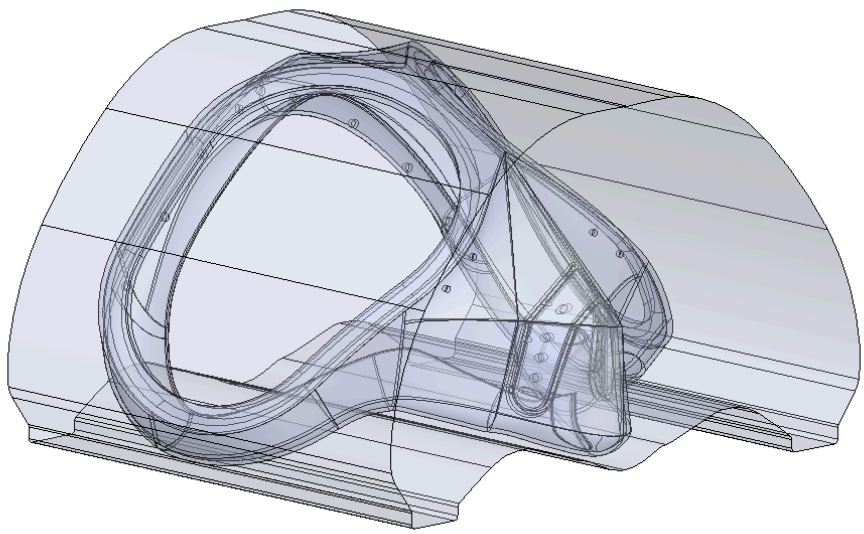


Fig: Mold with Stable Base for LSR injection, Nice to Have but Not Strictly Necessary

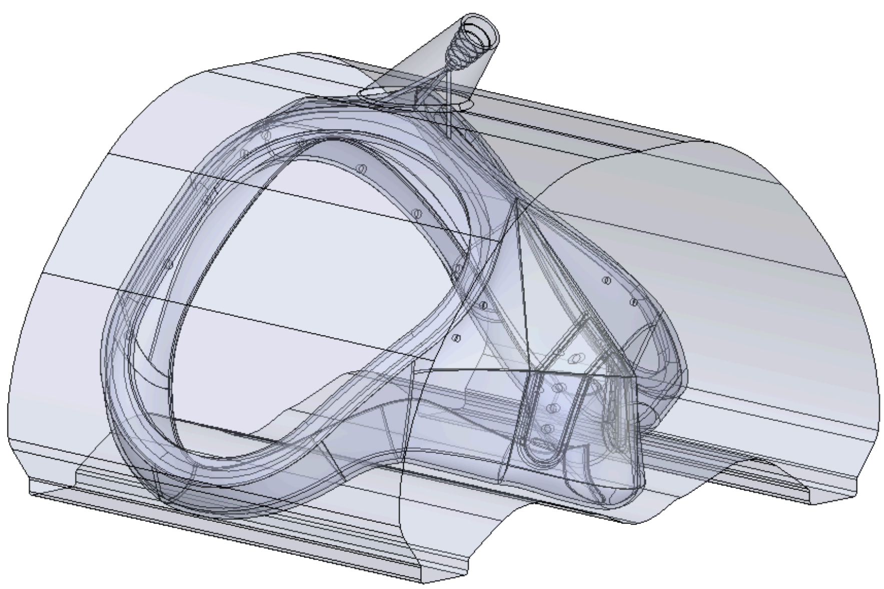


Fig: Mold with Fill Port

Vent holes to allow trapped air must also be added. This can be done in a similar fashion to finding islands. Cross section perpendicular to the base, when the mold is shot, and look for air pockets where air might get trapped as the mold is filled.

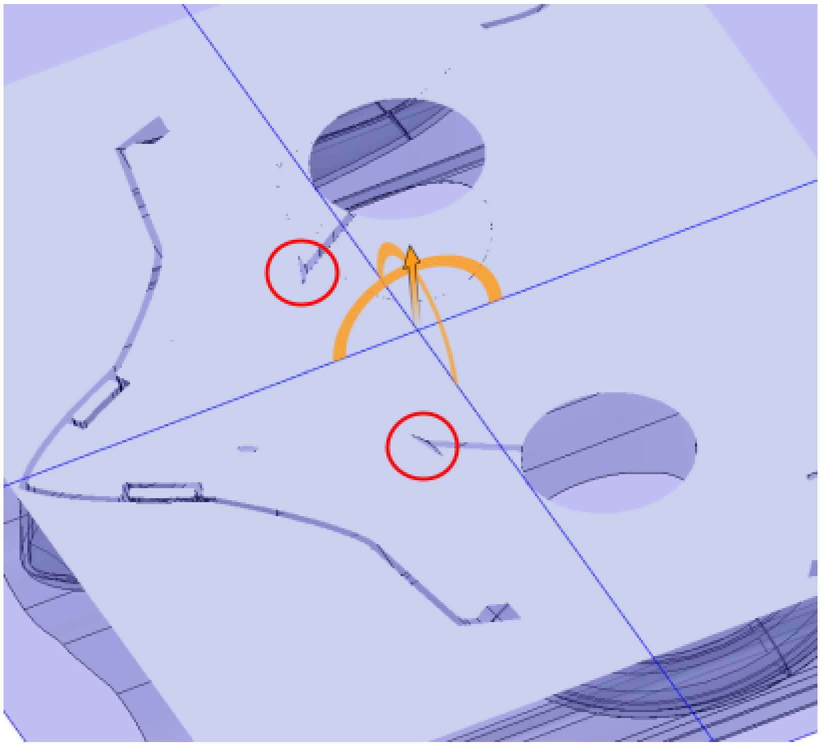


Fig. Air Pockets Highlighted in Red, Vent Holes Connect Them to Exterior Surface of Mold

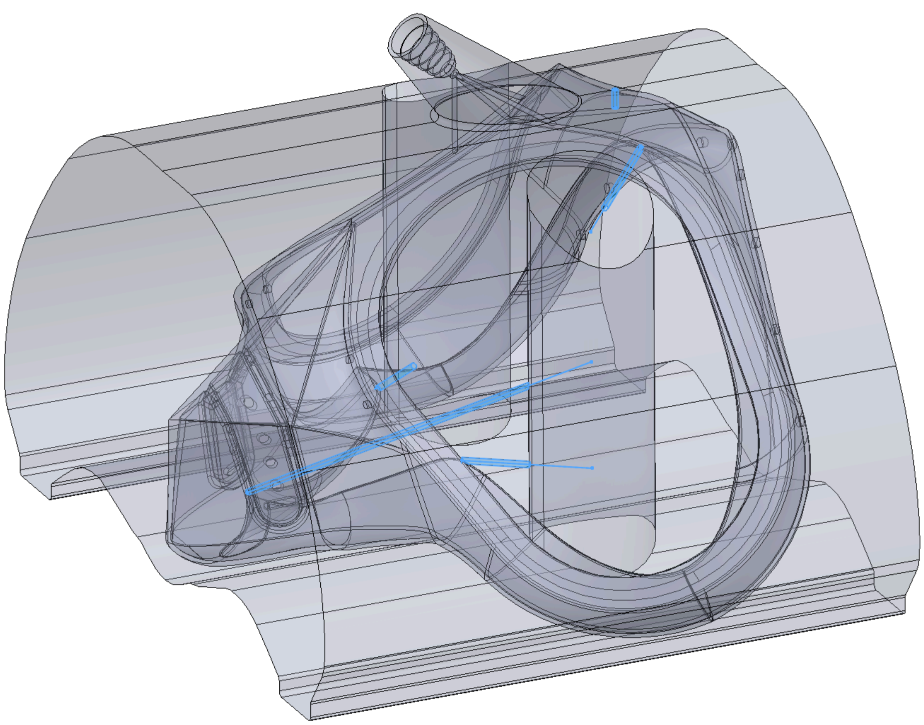


Fig. Blue Highlighted Areas are Vent Holes. Allowing Trapped Air to Exit Mold during Filling.

Respirator Filter Mold Creation

Mold Type

For the respirator filter mold we will be using a traditional clamshell style mold with a pair of side facing cores and a pair of top and bottom cores. We cannot use the same method as the respirator body because the filter medium cannot be immersed in water to dissolve the mold body.

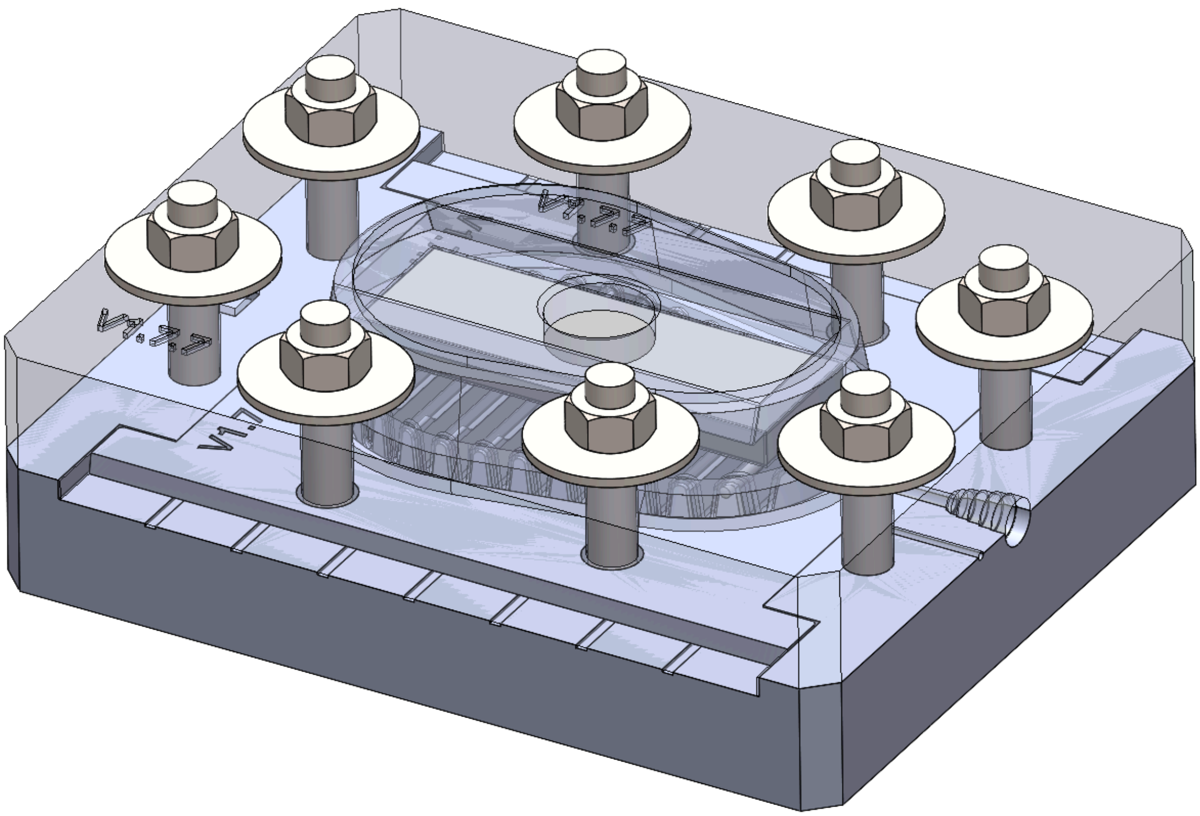


Fig: Respirator Filter Mold

Mold Body Design

The filter is designed to be molded in its flat state and conform to the respirator when installed. The 5 piece mold body was designed using Solidworks mold tools. A pleated filter assembly is inserted into the mold body and the side cores and top are added. The top and bottom of the mold hold the pleated filter assembly in place and the whole mold is held together with some standard bolts and nuts.

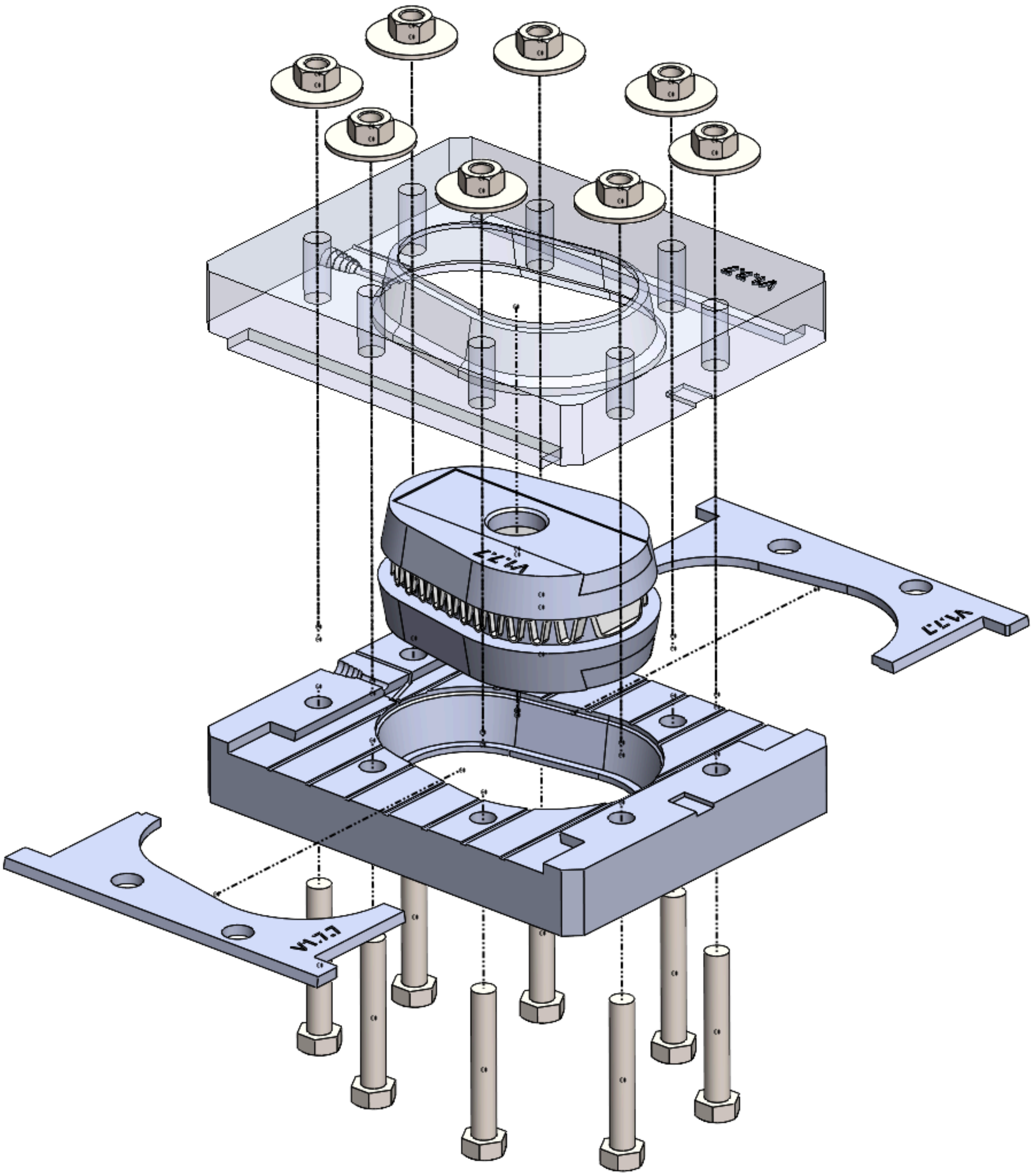


Fig: Filter Mold Exploded View

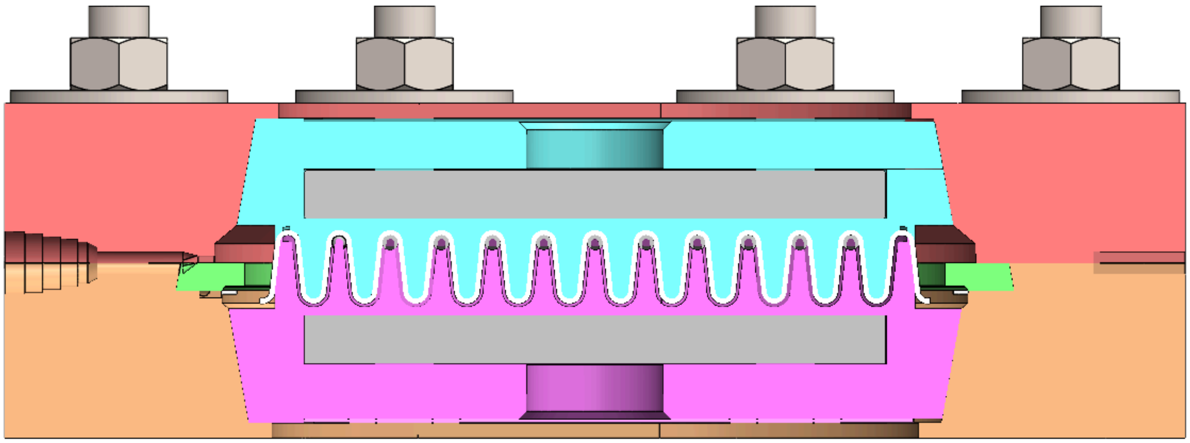


Fig: Filter Mold Cross Section with Filter Media

The pleated filter assembly consists of an upper and lower core with shutoff surfaces that hold the filter pleating in position. A large bar magnet is housed inside the upper pleated core. The three layers of filter media are inserted into the upper pleated core using a jig and each pleat is held in place with a steel pin that is attracted to the magnet. The lower section of the pleated core contains another magnet so once the two sections are brought together they hold the filter media in the correct shape for molding.

Respirator Filter Pleating

A simple jig was designed to create the pleat in the filter media and hold it in the pleated configuration so it could be correctly positioned in the mold for the silicone over molding process. The upper pleated core is used in this jig and can be transferred to the filter mold when the process is complete.

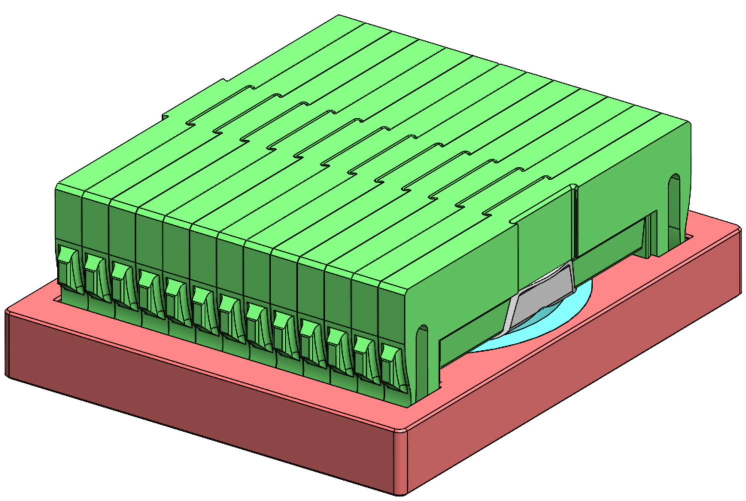


Fig: Filter Pleating Jig

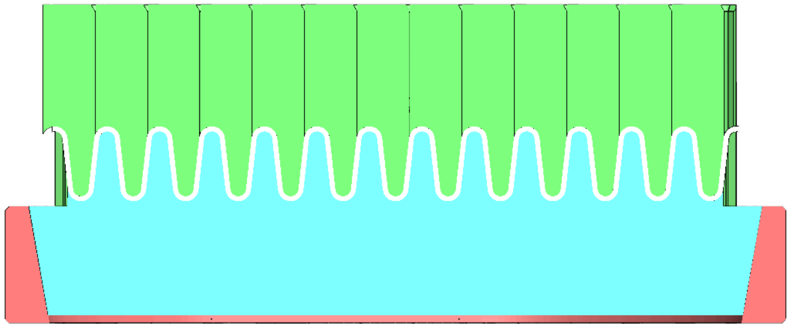


Fig: Filter Pleating Jig Cross Section

Respirator Manufacturing Process

Tools Used

- 3D Printers: Bambu Carbon X1 with AMS, Prusa XL 5 Tool
- 3D Printer Filament: BVOH, PETG, PCL
- Filament Dryer: PrintDry
- Liquid Silicone Rubber: Smooth-On Body Double Standard Set Silicone Rubber, Manual 1:1 Dual Cartridge Gun
- Heated Water Bath: Anova Precision Insulated Container, Anova Precision Cooker Pro

Respirator Body Manufacturing

3D Printer Considerations

Two different 3D printers were used in this process. For single and dual material molds that did not include PCL a Bambu Carbon X1 was used to print the mold. The X1 Carbon excelled at single material molds made from just BVOH. The X1 wasted a lot of material due to purging when two material molds were printed. PCL could not be printed, in multi material molds, on the X1 Carbon due to an incompatibility with the AMS system.

The Prusa XL 5 tool 3D printer was used to print 3 material Molds using BVOH, PETG, & PCL. Since the materials loaded in each print head do not need to be loaded and unloaded between material changes much less material was wasted and PCL was able to be incorporated into mold. This allowed us to co-mold both PETG stiffeners and a PCL nose bridge support into the silicone respirator body.

Slicing

Whether printing a single material or multi-material molds, the process was straightforward. Pictured below are images from Prusa Slicer. Most parameters were left stock for the PETG and BVOH profiles. Speeds were slowed down to ensure better adhesion between dissimilar materials. All layers were printed at 0.15mm layer height with a 0.4mm nozzle to achieve a reasonable final surface finish. The BVOH was printed with 3 perimeters for strength to withstand injection pressure from the silicone. It was also printed using Lighting infill to reduce filament consumption. We developed our own PCL profile, which we provide in our documentation. PCL is printed at 100% infill so that a solid piece of PCL can be melted and reshaped as needed once the silicone has been over-molded.

When printing with multiple materials on the Prusa XL we recommend setting the priming tower extruder to BVOH or there can be some material adhesion issues at layers with tool changes.

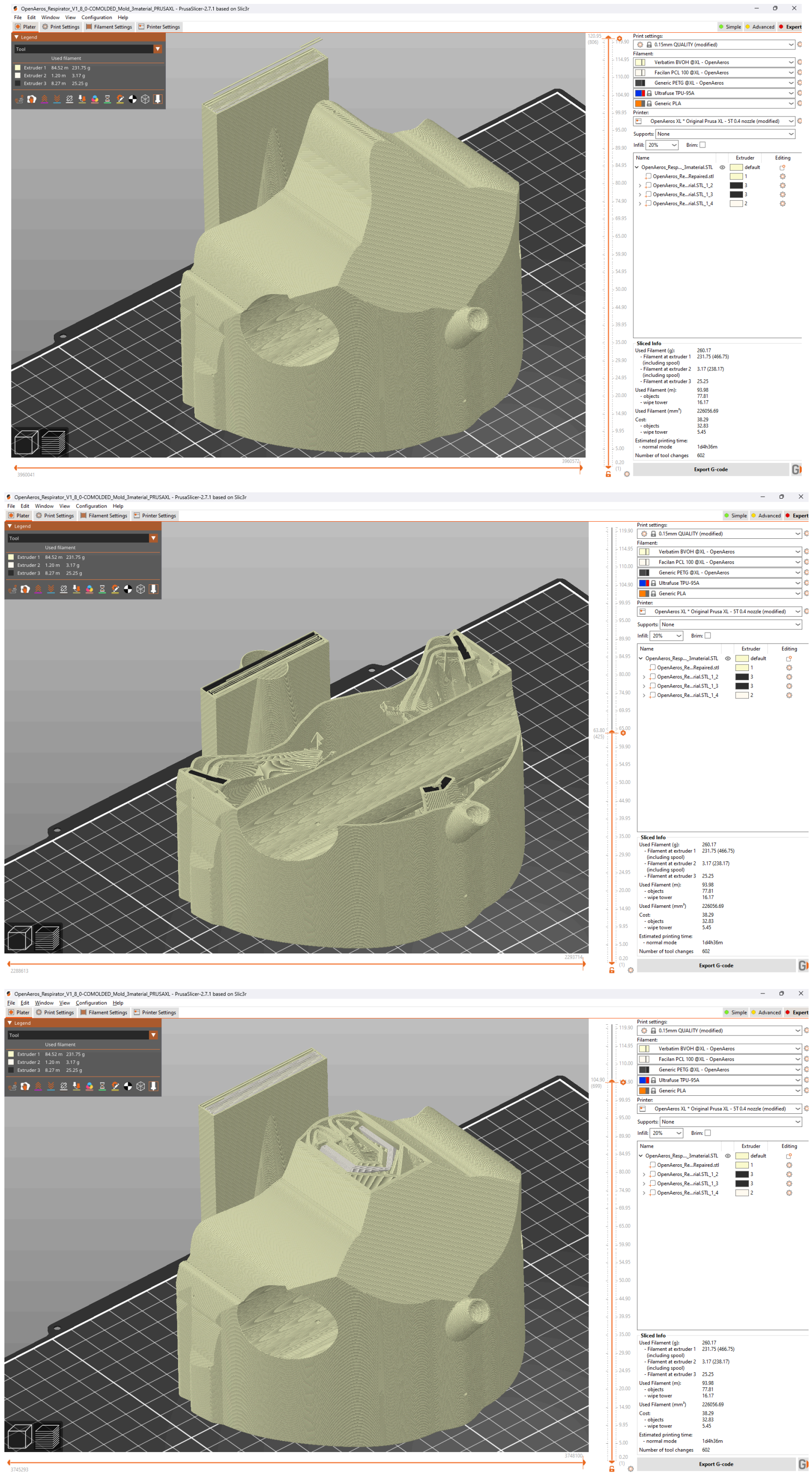


Fig: Slicing Section of 3 Material Mold in Prusa Slicer

3D Printing

As mentioned above the Prusa XL 5 tool and the Bambu Carbon X1 were used to print the Respirator Body Molds with the XL workling best for multi-material printing.

The BVOH and PCL were printed directly from a dry box on the XL and dried before each print on the X1 Carbon.

Fig: 3D Printers used to Print Respirator Body Mold, Prusa XL & Bambu Carbon X1

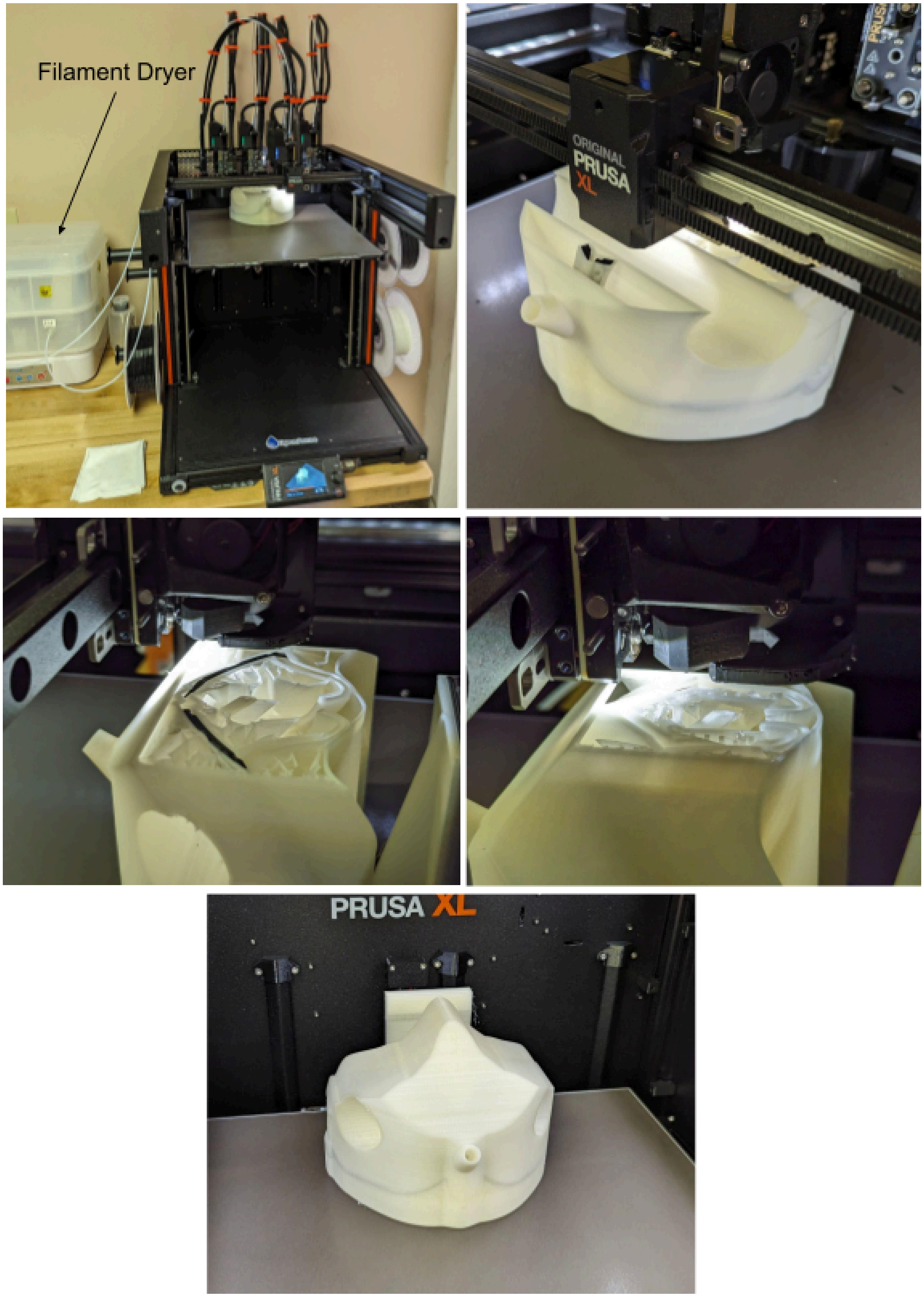


Fig: Three Material Mold Printing on Prusa XL 5 Tool

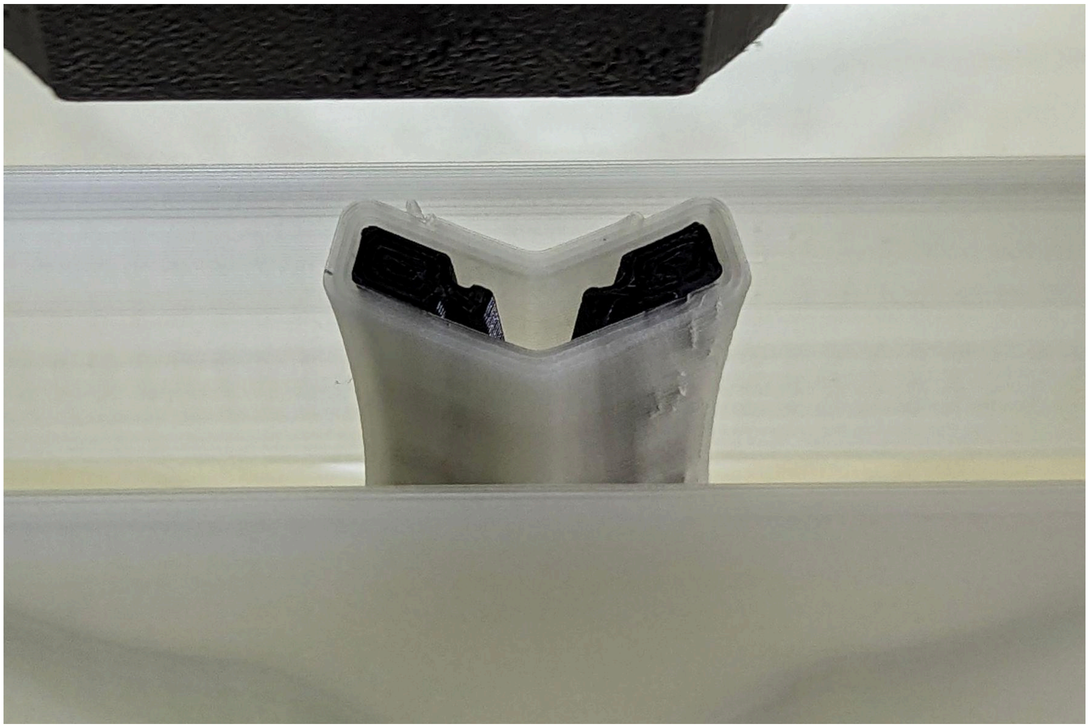


Fig: Three Material Mold Printing on Prusa XL 5 Tool, Close up of PETG Stiffener inside of BVOH Mold During Printing

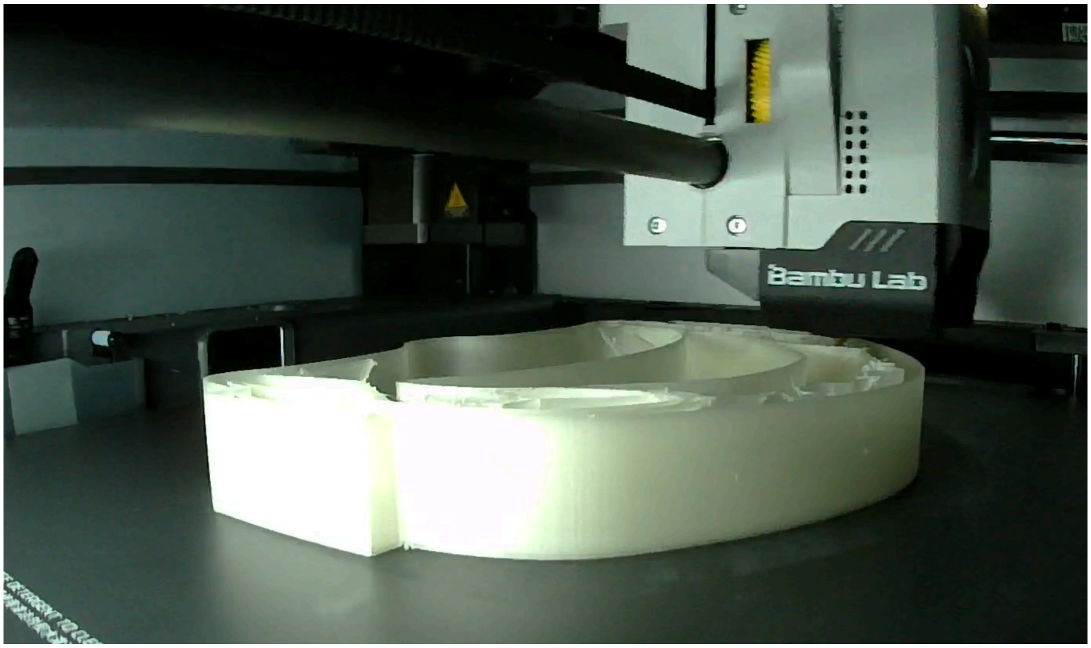


Fig: One Material Mold Printing on Bambu Carbon X1

Injecting Mold

Molds are filled using a manual dual cartridge gun with a 1:1 ratio for the Body Double silicone used in this process. Silicone is injected slowly until the entire mold is filled and silicone can be observed leaking out of the vent holes. Cure time is 30 minutes for the material we used and then the mold is ready to be dissolved.

Fig: Injecting Mold with Manual Handheld 1:1 Ratio Dual Cartridge Gun.

Fig: Mold after Silicone Injection (second Image has bottom layers removed to view interior of mold)

Dissolving Mold

The BVOH molds are dissolved in water using a heated water bath. An Anova Precision Insulated Container and Anova Precision Cooker Pro were used as a low cost heated bath. Temperatures of 60-80C work well to speed the process. Masks are soaked for 1-2 hrs and removed from time to time to clean away material that had come loose.

Fig. Heated Water Bath for BVOH Removal

Filling Support Holes

The 3D printing process requires support be added in certain locations in the mask mold, this leaves holes in the Silicone mask body. These holes need to be filled to ensure filtration performance of the respirator. The same silicone used on the respirator body is used to plug the holes. It is manually dispensed over the holes and smoothed with a finger. Any extra silicone can be trimmed away with some side cutting tweezers.

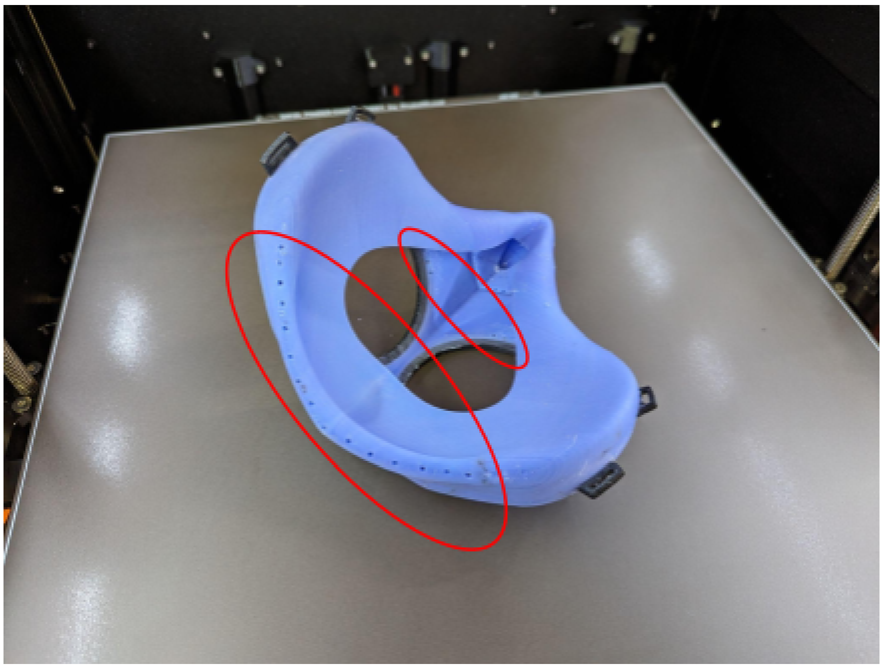
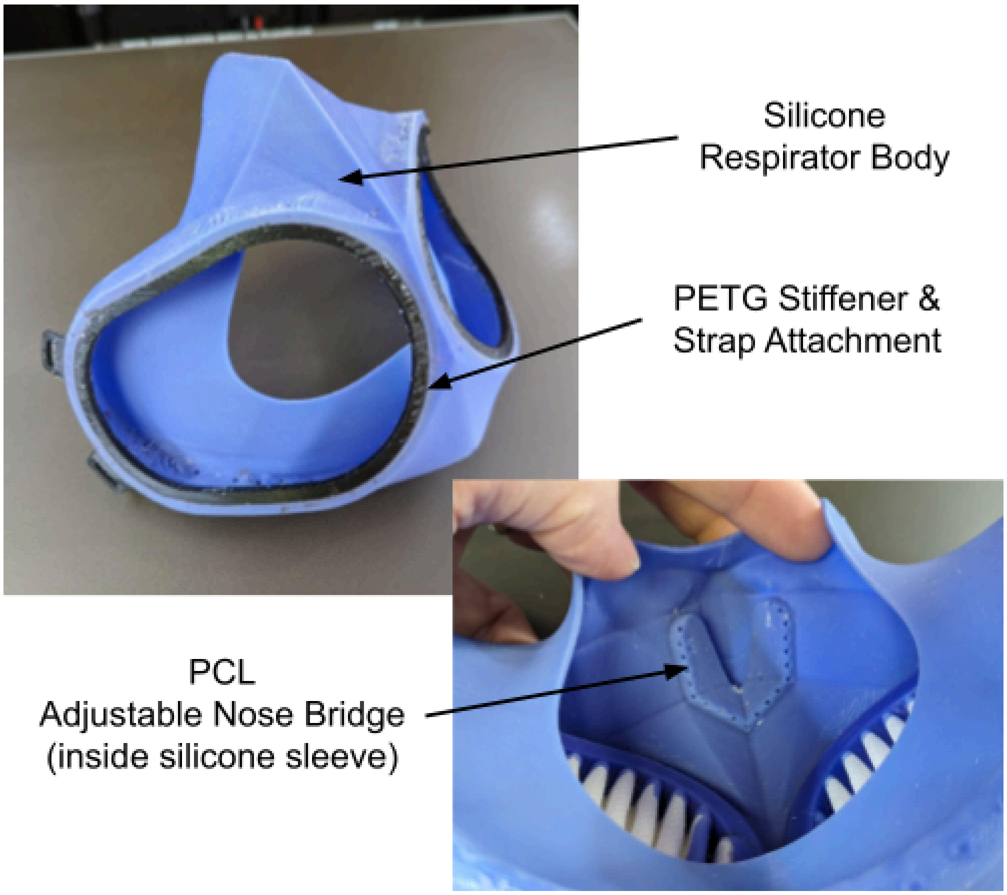


Fig: Filter Mold Support Locations Left Holes in the Silicone Respirator Body

Fig: Holes Filled with Silicone by Hand

Three Material Elastomeric Respirator

The images below show the results possible with this molding method. Functional components can be printed in place out of multiple materials inside the mold and then over-molded with silicone.



Filter Manufacturing Process

3D Printing

The Filter Media Pleating Jig and the FIlter Mold was 3D printed from PLA on a Bambu Carbon X1. Special care should be taken during slicing to ensure the outer shutoff surfaces around the filter media print well. This means that layer seems should be located away from shutoff surfaces to ensure the surface finish is as smooth and consistent as possible. Layer heights were also reduced as low as possible in critical areas also to improve surface finish. Ironing was also employed to improve surface finish.

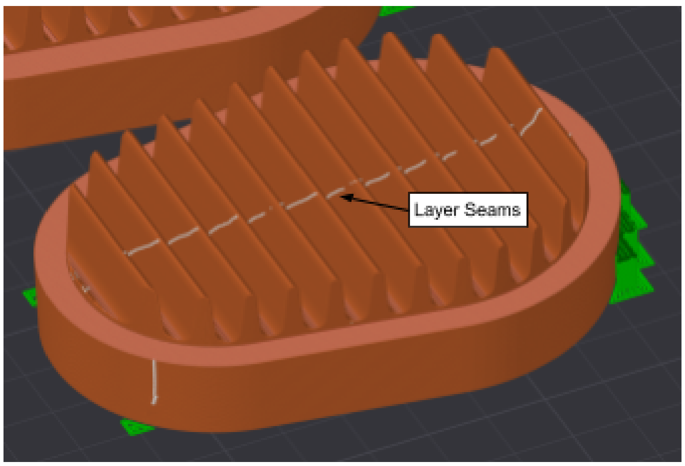


Fig: Layer Seams Positioned Away from Outside Edges to Insure Smooth Shut Off Surface

Media Blanks

To create Filters for the respirator a cutting template was created by flattening the surface from the midplane of the pleated filter media model. The resulting flat surface was thickened and 3D Printed to allow manual marking and cutting of the individual layers of filter media to create media blanks. The filter media was created from two outer layers of 60g/m², 0.39mm thick, needle punched spun bond and one inner layer of Hollingsworth & Vose AlphaPERM, P/N:13030AP2.

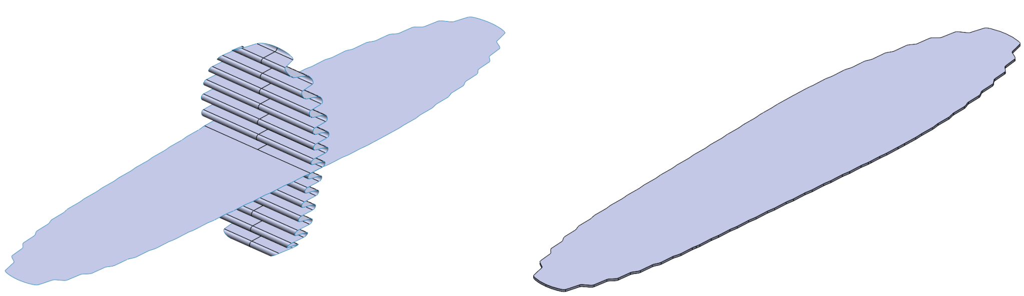


Fig: Media Cutting Template, Flattening of Pleat Surface in Solidworks & 3D Printed Template

Pleating

The three layer media blanks were then inserted into the Media Pleating Jig. Starting at one end of the jig a pleat insert is inserted into the jig forcing the media into the groove of the mold core. The remaining inserts are inserted one at a time. Once completely installed the inserts are removed one at a time and a steel pin is placed against the media at the bottom of each groove. They are held in place by the magnet in the bottom of the mold core and keeps the filter media from coming back out of the mold core. When all pins are in place the other half of the mold core can be placed on top holding the filter media in place for molding.

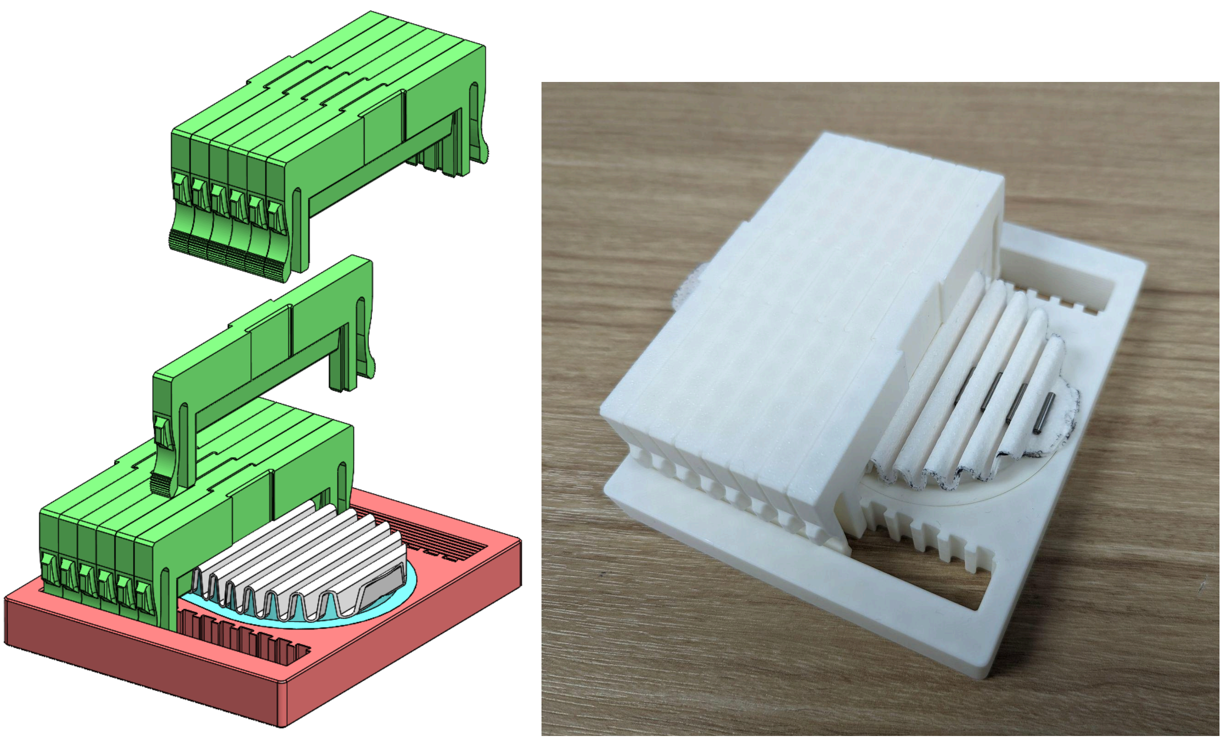


Fig: Media Pleating Process using Jig

Fig: Filter Media Held in Place by Top and Bottom Cores

Assembling Filter Mold

The filter mold is assembled by adding Filter media top and bottom core assembly to the lower section of mold. The Side cores are then inserted followed by the top section of the mold. The two halves are clamped with bolts and the mold is ready for LSR injection.

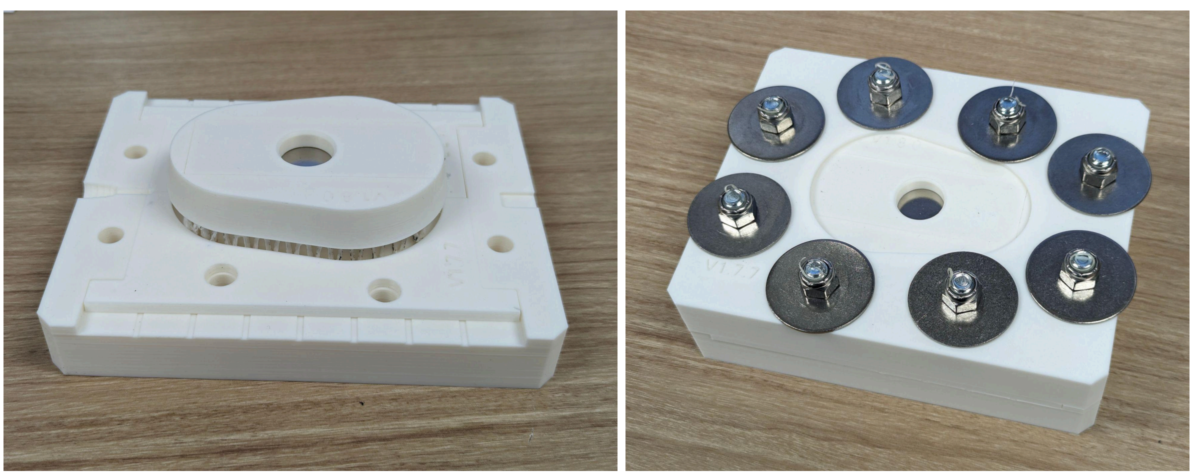


Fig: Top, Bottom, & Side Cores Installed, Fully Assembled Mold

Injecting Filter Mold

The LSR injection process for the filter mold is very similar to the respirator body mold. Once fully assembled the mold is filled in a vertical position. Care should be taken to minimize internal silicone pressure to avoid unwanted flash. Getting reliable shutoff surfaces around the filter media and preventing flashing of silicone into the media is an ongoing challenge. This was improved by adding additional direct clamping of the top and bottom cores that hold the filter media.

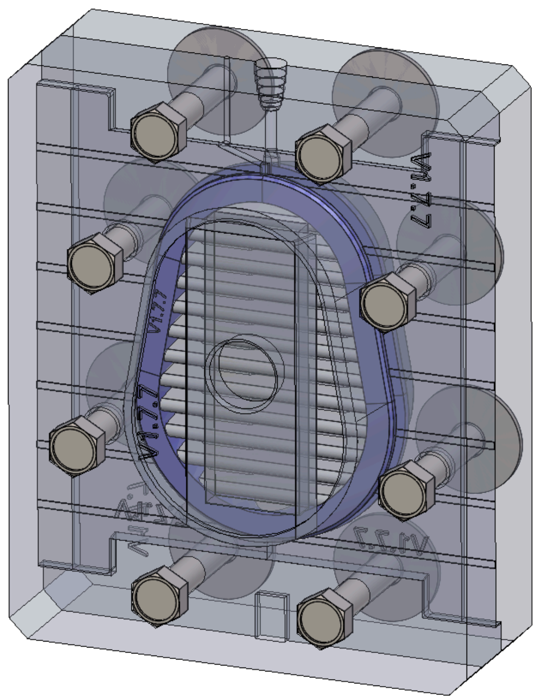


Fig. Filter Mold in Vertical Filling Orientation

Once the LSR is cured the mold can be disassembled and the over molded filter removed. Flashing can be trimmed and the filters can be installed in the respirator.

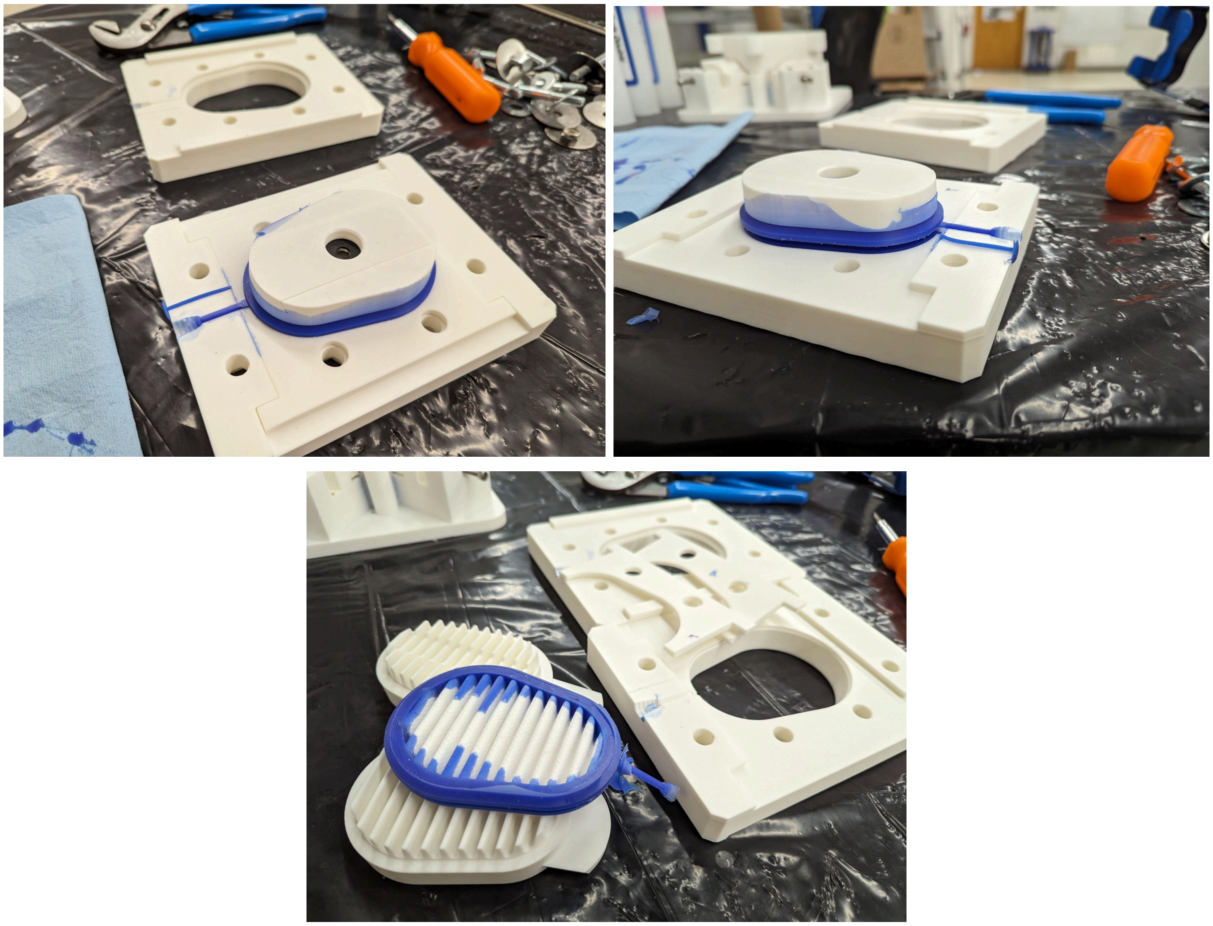


Fig: Filter Mold Disassembly After Injecting Silicone

Fig: Final Overmolded Filter

Final Process Prototype

Using the OpenAeros OpenCPC mask fitter the OpenRespirator was tested and achieved over a 99.97% filtration efficiency as worn.

Fig: Fit Testing the OpenRespirator

Fig: Prototypes Created During Process Development

Fig: Initial Fully 3D Printed Prototype, Functional Elastomeric Respirator Prototype

Fig: Final Fully Functional Elastomeric Respirator Prototype