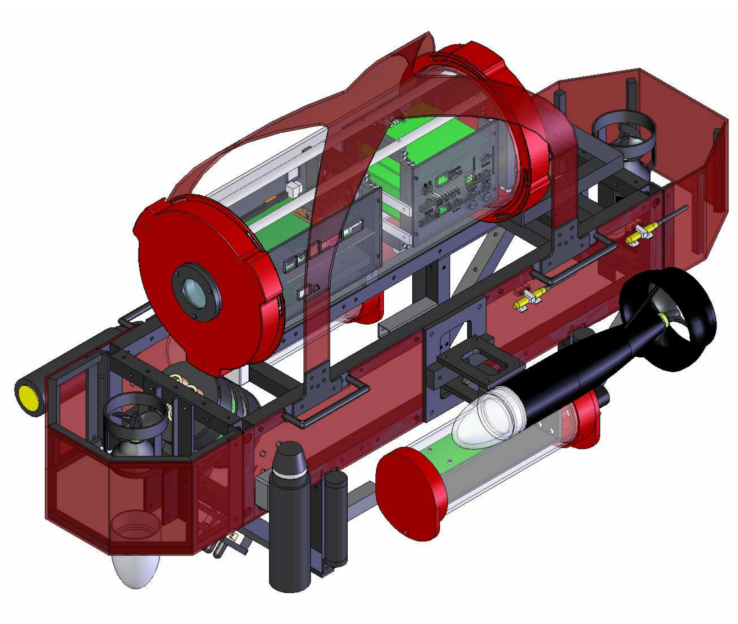
Cornell University Autonomous Underwater Vehicle Team: Sealing Manual and Protocols



CUAUV

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2008

CUAUV Sealing Manual

I. Purpose

The purpose of this manual is to gather together the accumulated experience of CUAUV relating to sealing underwater pressure vessels, both for future team members and new teams to the AUV competition.

II. Characteristics of different types of o-ring seals based on the experience of CUAUV:

The Cornell University Autonomous Underwater Vehicle team has primarily uses face and bore seals. We have had both successes and failures, and below are descriptions (and advice for successful implementation) of both bore and face seals.

Bore seals:
A bore seal is a seal where the o-ring is on the surface of a cylinder fitting into or over another cylindrical sealing surface. There are two types of bore seals, plug and endcap. A plug bore seal, which we have used extensively, has the o-ring cut into the plug from the side and the cylindrical bore seals around it on the outside. An endcap bore seal has the o-ring cut on the inside of a cylinder and the bore seals to the inside. The reason we use plug bore seals has been because they require less specialized tooling to cut in small diameters.

Used by:
- Triton (2007-2008)
- Seamonkey (2004-2006)

Terminology used in parker o-ring handbook:

Bore diameter- the diameter of the endcap or cylinder the plug is sealing into

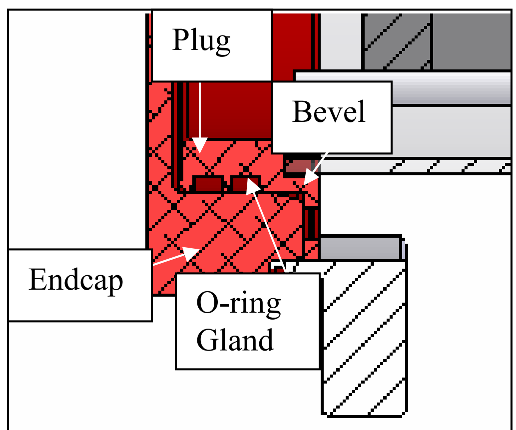
Endcap- the cylinder that the plug fits into in order to seal.

Plug diameter- the outside diameter of the plug

Male o-ring gland- the o-ring gland is cut into the plug.

Female o-ring gland- the gland is cut into the endcap.

*In this documentation the "endcap" surface of a plug bore seal will sometimes be referred to as the bore.



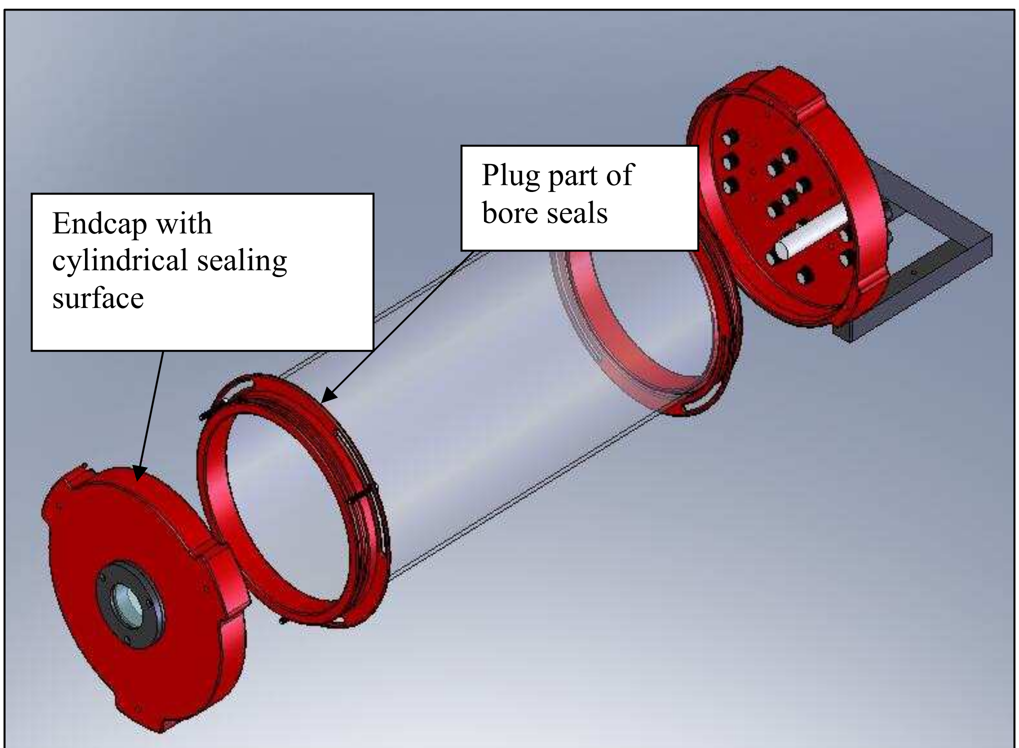
Triton plug type bore seal, with bevel and double o-ring gland

Using different types of plug bore seals:

We have implemented plug bore seals both with the endcap as the plug and a hull or hull collar as a bore and with a hull collar as a plug and the endcap as a bore. The triton battery pods are an example of the first and upper hull is an example of the second. Which you use is dependent of that amount of space available.

We prefer to use hull collars to hulls as the bore in the cases where the plug is the endcap because it allows us to incorporate a bevel into the bore.

Triton Battery pod bore seal. A case where the endcap contains the o-ring glands.



Front and back double bore seals on Triton, the CUAUV 2007-2008 competition vehicle using the hull collar as a plug and endcap as a bore

Use Of Bore seals:

Bore seals seem to be very dependable from a sealing standpoint. They are not finicky, and do not leak as easily as *Pros and Cons* face seals. Here is some advice we have accumulated on using bore seals:

- Very tight seals: hulls with bore seals can be difficult to seal/unseal because the seal is so tight. The guidelines given by the o-ring handbook are for far higher pressures than we work with, so the seals are far tighter than necessary. For example, the Triton hull was originally designed with a double bore seal, but proved so difficult to open/close that only a single o-ring is used, and it requires a screwdriver to pry open and progressively tightened bolts to close.

- If any air leaks out (because of pressure relief valves etc.), the hull becomes almost impossible to open. A similar affect is noticed if the hull is sealed in a warm or wet environment than brought into a cooler one, as the air decreases in volume, again causing difficulties with unsealing. Our solution in Triton to this is a face sealed viewport in the front which allows us to equalize the hull if necessary.

- Tolerances are very important: if you have a bore seal plug going into an endcap, it is essential that the plug be smaller than the endcap. In machining, it is very important to note this and adjust tolerances accordingly. The result of a plug that is too large is o-ring extrusion.

- While o-ring grease is important for bore seals, it is less essential than for face seals for sealing. However, it is very helpful as lubrication to help parts go together.

- The greatest worry with these o-rings is extrusion, so be sure to always check o-rings for tearing.

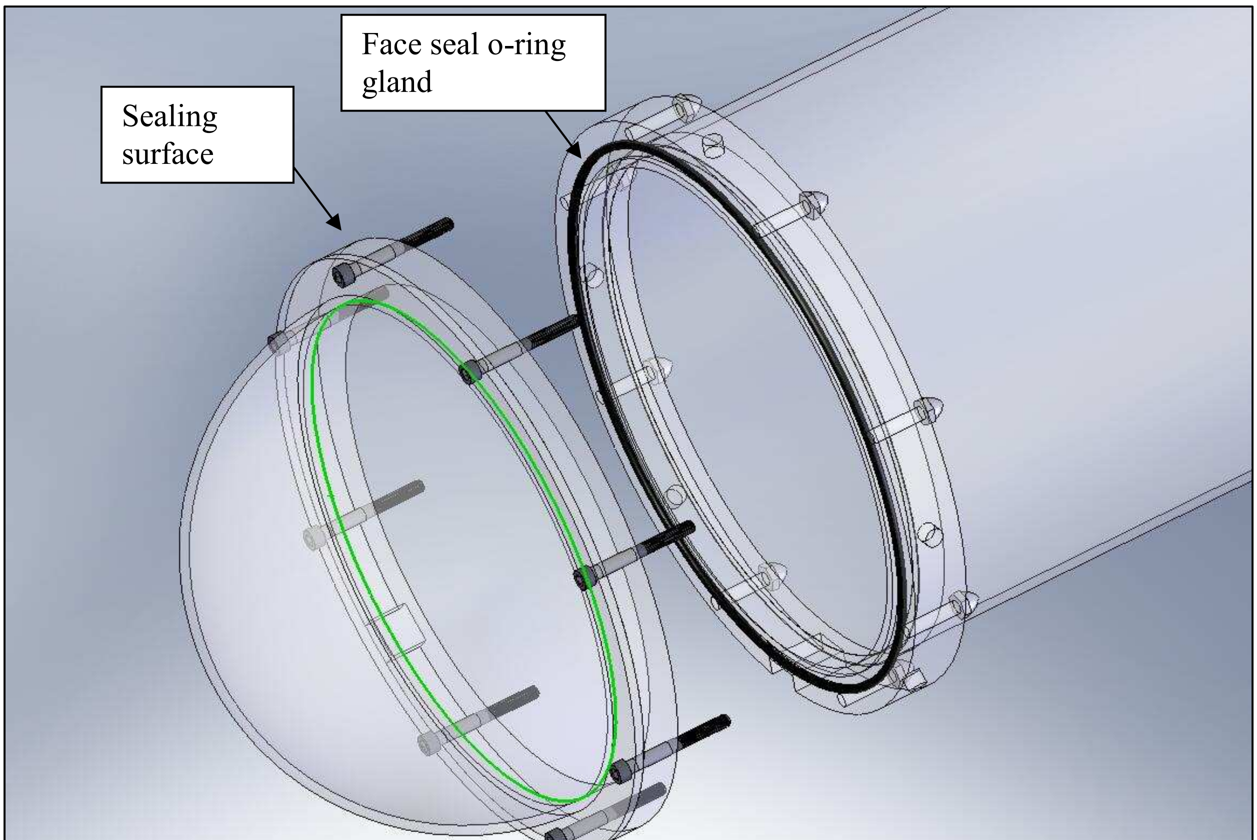
Hull of Triton, with front endcap engaged. A case where the sealing collar contains the o-ring gland.

- To decrease the occurrence of extruded o-rings and make getting the seal apart easier, include a 10 degree bevel to help compress the o-ring

Face seals:
Face seals use an o-ring gland in a flat surface to seal to a second flat surface. The tolarancing and dimensions are done in a slightly different manner than bore seals, because it matters whether the pressure is internal or external. For underwater pressure vessels, the pressure is externals, and the dimensions you would need to use are listed in the section on interpreting the parker o-ring handbook. You design using the mean ID of the o-ring, and cut your gland accordingly.

Used By:

- Seamonkey Misc. sensors (2004-2006)
- Proteus (2006-2007)
- Triton Viewport (2007-2008)



Front face seal of Proteus, the 2006-2007 CUAUV competition vehicle. The acrylic hull collar contains the o-ring, and seals to an acrylic “flange adaptor” which is epoxied to the dome. Eight #10-24 screws make sure that the seal cannot lift up.

Using face seals: Pros and Cons

Face seals can be very reliable if properly implemented. They require many points of pressure to seal properly, and can be easily disengaged. They require a larger surface area than bore seals and more points of attachment. However, they are very easy to engage/disengage, requiring little force as compared to a bore seal. They are more reliable if you are pulling a vacuum on the pressure vessel. But in our experience, they can be extremely finicky and difficult to make work if they are not well thought out. Here is some advice of when and how to use them.

Proteus Upper Hull.

Proteus in the water at TRANSDEC

- Make sure you have enough attachment points: face seals will lift and unseat pretty easily, so it is important to make sure they are supported all the way around. For a small face seal, such as the viewport in Triton (3” diameter), three bolts is sufficient to hold down the seal. However, we encountered difficulty with the Proteus face seals (7” diameter) with our original plan of three attachment points. In the end, we had five, which worked fairly well.

- Make sure the hull cannot lift up: Even with the five attachment points, our cantilever rack design allowed the hull to lift up with respect to the endcap, causing the seal to “glug”, allowing a great deal of water to enter the hull. The solution to this was a heavy rubber strap that held the hull down against the frame of the vehicle.

- There is no such thing as too tight: just so long as you do not strip the screws you are using to bolt together your seal, get it as tight as possible. Looking at the seal from the side, you should not be able to see a crack between the two surfaces.

- Tolerances for o-ring glands: While bore seals are at least a little forgiving with respect to the smoothness of o-ring glands, face seals do not appear to be so. When setting your tolerances for machining, assure that the inside diameter of the gland is not too small, or the gland will not seal.

- Sharpen your trepanning bit: because the face plate and gland surface wind up being flush in a face seal more so than in a bore seal, make sure that your gland does not have burs on the edges. The best way to ensure this is to make sure your trepanning bit is sharp and you are turning at the right speed.

- Materials: do not use acrylic for anything structural in your seals. We have used acrylic hulls for both Proteus and Triton, but apart from that we have avoided acrylic sealing collars after our experience with Proteus. We had a lot of problems with cracking and material failure, as well as epoxy problems attaching acrylic to acrylic. Triton has aluminum sealing collars epoxied to acrylic hulls. The slight reduction in weight of acrylic from aluminum is not worth the risk of material failure. Similarly, we now avoid using flexible plastics like HDPE as any part of face seals because they deflect and can cause a "glug" leak.

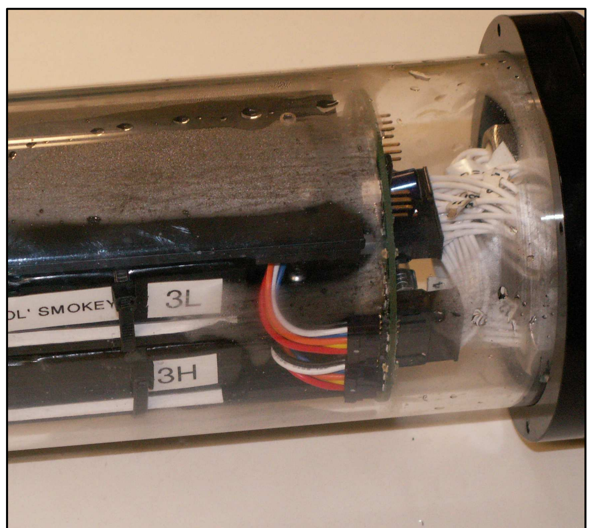
- Use a lot of o-ring grease. Face seals that will not seal without o-ring grease seal perfectly with it. So if it does not seal at first, add a lot of grease.

- It is extremely important to keep face seal o-ring glands clean of all grit and debris.

Leaking Face seals:

When not held tight enough, face seals leak very easily and quickly.

Leaking on back face seal of Proteus during the multiple design changes needed to make the upper hull seal



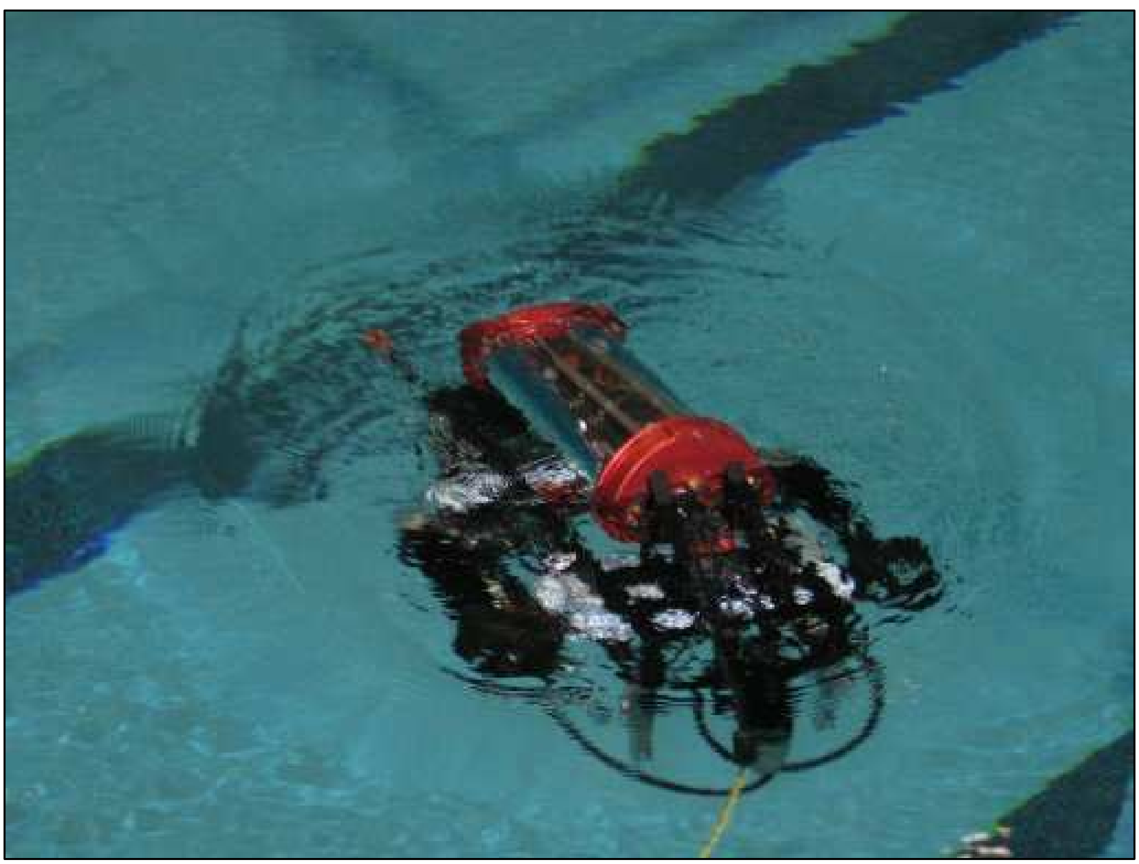
Leaking into Proteus battery pod due to improperly tightened face seal.

Team decisions regarding sealing type:

The 2004-2006 vehicle, Seamonkey, had bore seals. However, these were so difficult to disengage that it took several people pulling or pushing to take the hull on/off. The team elected to switch to face seals for the 2006-2007 vehicle to alleviate this problem, which would make the new cantilevered rack system difficult to implement.

The difficulties encountered with sealing Proteus were mostly due to inexperience with face seals. We learned (through a lot of fried electronics) how important it was to make sure there are enough secure attachment points to hold a face seal o-ring in compression. Even once we had enough secure attachment points, human error in tightening down seals lead to several fried battery pod boards. Because of these problems, we decided to switch to bore seals for the 2007-2008 vehicle.

We worried about having this same problem with the 2007-2008 vehicle as had been encountered with Seamonkey. We obtained advice from people at Wood's Hole Oceanographic Institute to include a bevel at the beginning of the seal, to allow the o-ring a more gradual compression. We hoped that this would help. In the end, the double bore seal in the original design proved too difficult to force closed/open, so only the single back o-ring was used. In the battery pods, softer o-rings made the bore seals far easier to take apart and put together. Unfortunately, softer o-rings did not exist in the size needed for the upper hull. The bevel made some difference, but a gentler bevel might be used in later years to further ease the problem. However, the advantage of these tight seals is that there have been no sealing problems with any of our pressure vessels on Triton.



Interpreting the Parker O-ring Handbook:

http://www.allsealsinc.com/parker/static-oring-sealing.pdf

The best source for determining dimensions of o-ring seals is the Parker O-ring handbook. It explains how to make many types of static and dynamic seals work properly. However, it is sometimes difficult to understand how to read the many different charts and diagrams, so below is a outline of the useful dimensions for design of plug type bore seals and face seals.

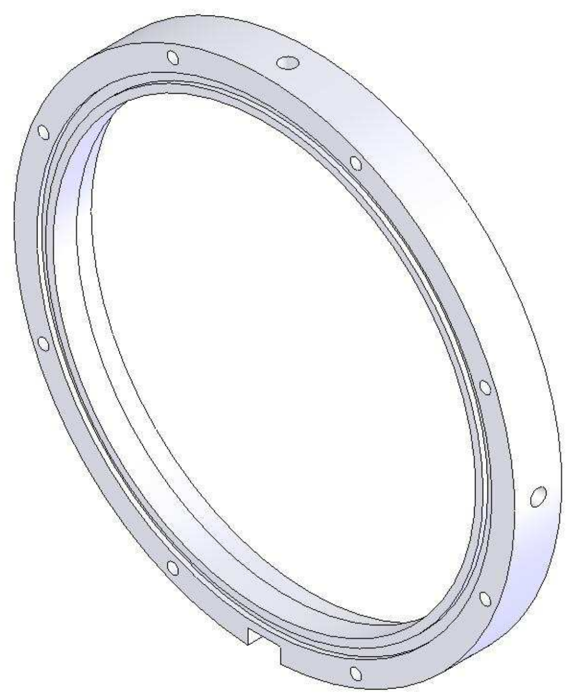
For plug type bore seals:

The dimensions of the gland are, from design table 4-1:
A is the ID of the endcap
C is the OD of the plug
B-1 is the diameter of the gland
L is depth of the gland
G is the groove width

Example: Triton Sealing Collar
A is 7.25 (ID of endcap desired)
B-1 is 7.028
C is 7.247
#262 o-ring
The trepanning bit would have a width of 0.187 +0.005 /-0.0
You would cut to a depth of .082 +/- 0.001

For face seals:

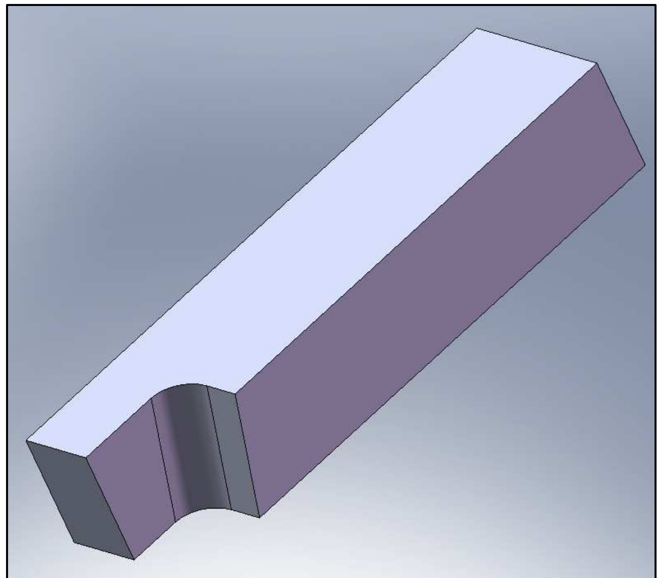
Use table on face seal o-rings, guidelines for external pressure
L is gland depth (depth of cut)
G is groove width (thickness of trepanning bit)
Use the mean ID of the o-ring as your gland ID, +/- 1% of the Mean ID



Example: Proteus sealing collar
O-ring must sit between 6.75 and 7.25 inches (diameter)
ID is 6.987
L is 0.077
G is 0.14

III. Cutting O-ring grooves:

To cut o-ring grooves, it is necessary to grind your own tools. This way, you can ensure that the tolerances and shape of the groove are what you want. This is further necessitated by the fact that, as far as we can tell, you cannot buy trepanning bits. Instead, you buy tool steel and grind your own.



Trepanning bit ground down to correct thickness.

Grinding Trepanning Bits:
The shape of the trepanning bit depends on what type of o-ring groove you are making and the specific part you are cutting. For example, there was one part that I made this past year that required a "backwards" trepanning bit because of characteristics of the part. But once you make one tool it is really easy to make others.

You work with a trepanning bit like a lathe cutoff or grooving tool. Like a cutoff tool, it is shaped with a flat, sharp top edge and a taper to one side for chip relief. (The side of the chip relief depends on the part and the groove, or you can relieve both sides.)

For most o-ring grooves, I start with 3/8" tool steel. Using a fine grinder, I cut sideways into the tool steel.

When grinding, it is important to hold the tool steel firmly down against the table. As it gets too hot to hold, drop it in a bucket of water to cool, and then continue. Don't wait to long to do this or you will wind up with blisters. As you come close to the final thickness, hold it for only a few seconds at a time against the grinder and measure until you are within .0005 of your final thickness (determined by the gland width in the parker o-ring handbook). Be sure as you do this to not slip and nick the top edge. While the tool can be resharpened once finished, I find it works better to leave the original edge of the tool steel in tact.

Four finished trepanning bits, two per 3/8" tool steel blank.

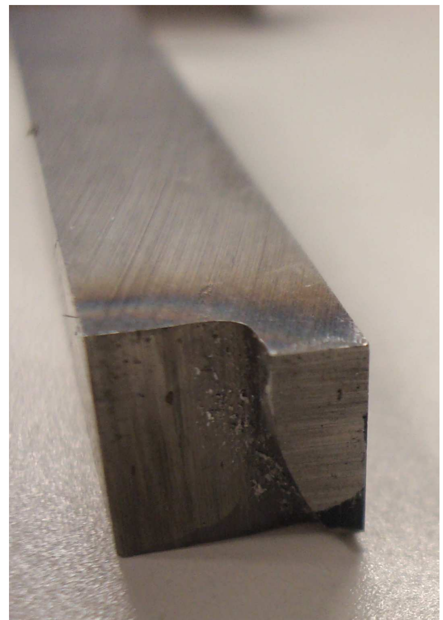
Once your tool is the proper thickness, you need to add the chip relief and radius.

For Face Seal o-ring glands:
Because you are cutting a round gland with a square tool, the side of the tool on the outer radius of the gland can drag and cause the gland to not be round. As with all lathe processes, you want the lathe to turn the part into the tool. Based on that, you need to

decide which side of the tool needs to be curved, and to what radius. The easiest way to do this that we have found is to line up the unrelieved tool with a drawing that shows the gland and determine where the tool would be cutting extra. You want to cut this relief to the radius of the outer diameter of the gland. The third cut is to curve the front face of the tool steel.

For Bore seal o-ring grooves:
Radius relief is not as important, but the front relief is more important. However, you can curve one or both sides of the bit for increased chip relief.

Cutting O-ring Grooves:
To ensure your seal does not leak, it is very important that your o-ring grooves be within tolerances set in the o-ring handbook. While we have seen that we have a little more leeway with bore seals, we have found that face seals need to be strictly within the dimensions of the o-ring handbook. The most important dimension for face seals is the inner diameter of the gland. Even if your tool is a little too large, make sure that that inner edge is as close as possible to the stated ID of the gland.



Front view of trepanning bit: shows shape of radius relief for face seal gland.

Cutting face seals:
Set up your tool in a tool holder so that it faces the part. Make sure it is not upside down, and that you have done your chip relief correctly (i.e. if the lathe is turning towards you and the tool is on the near side of the part, the relief should be closest to you). As mentioned before, the best way to check this is to hold your tool up to a 1:1 drawing of the gland. The entire front of the tool should fit within the gland. If this is not true, work some more on your tool until you are sure that the sides and bottom will not drag on the part.

The speed of the lathe depends on the material you are cutting. If it seems like you are melting the material, then you need to change speed. I usually use a slower speed for working with a trepanning bit than I do with a facing tool. Make sure the tool is centered up and down, or your gland will not come out very well (and you might damage the tool). Zero to the edge of the part side to side and then move the tool into the correct position. Make sure to take the thickness of the trepanning bit into account, or your gland will be in the wrong spot. As with all lathe parts, be sure to know what dimensions are in radius and which are in diameter, or it is really easy to mess up. I usually mark the part with the bit (lightly) then measure with a caliper to make sure the gland is in the correct spot. When you are actually cutting the gland, pay very close attention to how deep you have gone. A shallower gland, for face seals, is generally better than one that is too deep.

Once you have cut the gland, measure all dimensions to see if they are correct. If the gland is too deep or wide, or is in the wrong place, you are best off making a new part. If the gland is not deep enough, you can sometimes find it again and cut it to the correct depth.

Cutting Bore Seals

Set up your tool in a tool holder like you would set up a grooving or cutoff tool. Make sure it is not upside down. Bore seals are much easier to cut than face seals, as placement on the surface is generally less vital to their function. As mentioned before, the best way to check this is to hold your tool up to a 1:1 drawing of the gland. The entire front of the tool should fit within the gland. If this is not true, work some more on your tool until you are sure that the sides and bottom will not drag on the part.

The speed of the lathe depends on the material you are cutting. If it seems like you are melting the material, then you need to change speed. I usually use a similar speed to what I use for a cutoff tool. Make sure the tool is centered up and down, or your depth will be off. Zero to the front of the part, and go in the correct distance to where you gland will be cut (make sure to take into account the thickness of the tool). Zero to the surface you will be cutting into. As with all lathe parts, be sure to know what dimensions are in radius and which are in diameter, or it is really easy to mess up. I usually mark the part with the bit (lightly) then measure with a caliper to make sure the gland is in the correct spot.

Depth is the most essential part of a bore seal o-ring gland. A gland that is too deep will not provide enough of a seal, and a gland that is too shallow will cause the o-ring to extrude. When you are actually cutting the gland, pay very close attention to how deep you have gone. A shallower gland, for face seals, is generally better than one that is too deep because you can always cut it deeper. It is good idea when cutting plug o-ring glands to make sure the endcap you are sealing into is actually within tolerances. We had an issue with an endcap that was too small, and we had to rework the o-ring glands.

Once you have cut the gland, measure all dimensions to see if they are correct. If the gland is too deep or wide you are best off making a new part. If the gland is not deep enough, you can sometimes find it again and cut it to the correct depth.

Surface Finishes

All sealing surfaces should have a 32 micro inch finish (from parker o-ring handbook). Tooling marks, burs or roughness can make the seal less dependable, and in our experience face seals will not seal at all if the finish is not good. This finish can be achieved by polishing and sanding during the lathe process. We have had good results with anodized surfaces that were first finished. You can make an additional tool to your trepanning bit to cut the proper radius at the top of the gland (R in the face seal table), but we do not bother with this and it does not seem to make much of a difference. We do, however, debur the o-ring glands using files and sandpaper.

Small bore seal trepanning bit.

IV. Use of Silicones, Epoxies and Urethanes

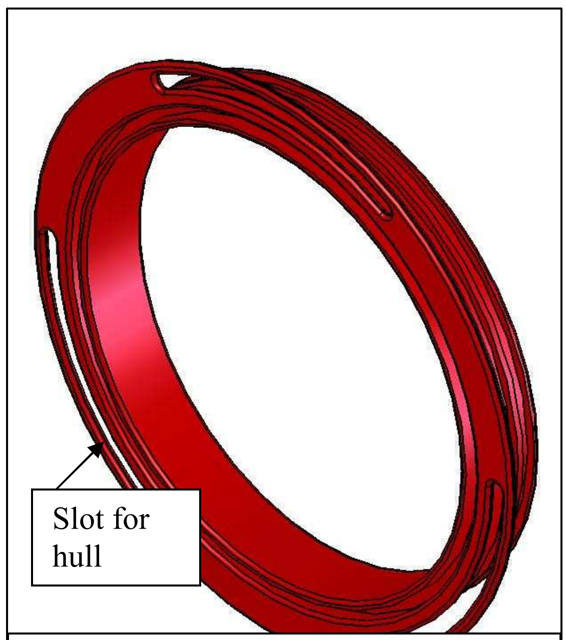
While we use o-ring seals in almost all of our pressure vessels so that we can easily access and maintain electronics, below are some of our experiences with silicones, epoxies and urethanes and brief descriptions of how we use them.

Silicone
We do not use silicone very often. The most common usage is for semiperminent gaskets in parts that do not have o-rings. In designs without o-rings, some work quite well to seal. However, silicone is not very good for anything that has a lot of stress put on it as it will stretch, break and peel away from surfaces. If you use it as a semiperminent gasket you need to scrape of the old silicone and reapply new every time you open the pressure vessel. Most of the silicones we use are 24 hour cure, which can be inconvenient when you need a quick seal as using the parts before the silicone is fully cured does not work. We are constantly on the lookout for ones with quicker cure times for emergency sealing fixes.

Epoxy
We use structural epoxy to seal and glue our sealing collars to acrylic hulls. The Epoxy we use is 3M DP-460 epoxy. It works very well to seal acrylic to aluminum, aluminum to aluminum, or acrylic to acrylic. It is a ugly yellow collar, but we find the aesthetic a good compromise for an epoxy seal that we know will not break or leak under ordinary usage. It has a high enough peel strength that it will not peel off of the acrylic as many other epoxies do. The only problem we have had with it was traveling to a pool test in 10 degree weather. The differences in contraction between the aluminum hull collars and acrylic hulls were enough to pop the epoxy seal in the battery pods. Because it is a structural epoxy, it can be used for a lot of applications outside of sealing as well.

The original epoxy used on Proteus, the 2006-2007 vehicle, was 3M DP-105 epoxy. We chose it because it was clear, but it quickly became apparent that it did not have a high enough peel strength for what we needed it for. We had numerous problems where it came away from the acrylic hull or hull collar, and the only solution we came up with was to add layers of epoxy and silicone on top, which did not work very well. Eventually all the DP-105 seals came apart and were replaced by DP-460.

We used DP-460 for epoxying hull collars to hull on Triton, the 2007-2008 vehicle. To allow for better attachment to the hull, the collars are designed with slots for the acrylic hull.

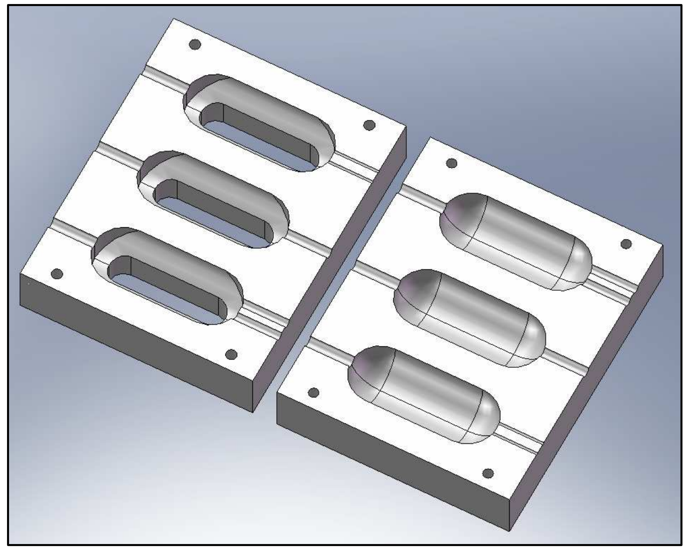


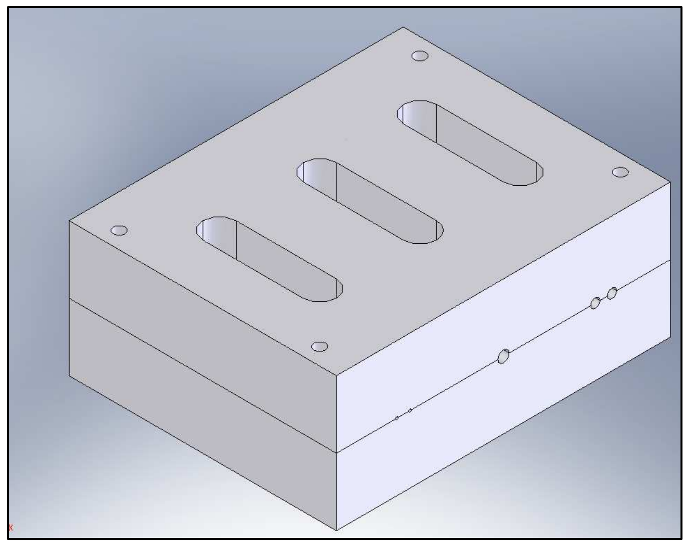
Triton upper hull sealing collar.

We also sometimes use the DP-460 as a potting substance when we are not confident that urethane will stick well.

Urethane

To pot underwater cabling, we mostly use 3M Electrical insulating resin for insulating power cable. It is black, so it blends in with the cable. We make potting blocks out of HDPE.





Keys to potting:

- Use a plastic like HDPE for your block: it is easy to mill and is slippery.
- When cutting out your mould, you can easily do it in one pass with a ball end millbit
- Rub o-ring grease into the mould so that the urethane will come out more easily.
- If you overfill the cavity you can cut off the extra part on top.

Two HDPE blocks make up the potting mould. The stock we used is 1” x 4” HDPE from McMaster-Carr.

To machine the blocks, we use a 1” ball end mill bit to a depth of 0.5”. A 0.5” mill bit is used to cut the slot in the top block. Four holes are then drilled in each block in the same regular hole pattern. The holes in the top block are #8 pass holes, and those in the bottom block are #8-32 tapped. Note the HDPE is self lubricating, so you do not need to use any machine oil.

The two blocks are bolted together using #8-32 screws, and the cables holes are drilled. Each cable being potted was measured, and a drill size was chosen as close to the measurement as possible. Slightly larger is better than too small. The bolted together block is set on end and drilled. More than one cable can be run in each side as needed, though more than two might require a slightly wider mould.

Once the block is finished, it should be cleaned, then both sides of the cavity smeared with o-ring grease. The wires of the cables are then soldered together and electrical taped. Test the electrical connectivity to ensure that the cables are properly soldered and not shorting. Once this is confirmed, place the cables in the correct slots of the mould and bolt together. Check the electrical connection once more.

Open the bag of insulating resin or urethane and follow the instructions. Pour your potting compound into the slots in the top of the block until it reaches the bottom of the slot (going higher will result in a bump on top of your symmetric bulb.) Let sit for 24 hours. When the block is removed, a symmetric blob of urethane is left surrounding the wire.

VI. Sealing Protocols

Resealing a hull that did not leak in the previous cycle:
For face seal o-rings
Face seals are really finicky. They will leak if the seal is even slightly out of alignment, or if there is anything protruding into the gland, or if you use too little o-ring grease. Therefore a great deal of care needs to be taken to maintain them, and every time they are undone these steps should be carefully followed:

1. remove o-ring from gland and set aside, using o-ring extraction tool if necessary
2. clean out o-ring gland entirely of grease and particulates using rubbing alcohol
3. clean off sealing surface of face entirely using rubbing alcohol
4. wipe off o-ring (being careful not to stretch it)
5. inspect o-ring for any tears or other discontinuities
6. If o-ring is in tact, not overly stretched, and has been used fewer than 10 cycles, it may be reused. Otherwise, get a new o-ring of the *correct* size.
7. Grease o-ring: dispense enough o-ring grease and pull it around the o-ring until it is completely covered.
8. Inspect the o-ring gland one more times for dirt, and clean again if necessary
9. Place o-ring in gland, ensuring it is fully seated in the gland. Be careful not to wipe away o-ring grease
10. Reseal, checking the sides of the seal (with a flashlight, if necessary) that the two parts are flush. Note: unless you are damaging the material that holds the face seal, there is no such thing as tightening too much.

For plug type bore seal o-rings
Bore seals are not finicky. The greatest danger lies not in them lifting up and unseating as it is for face seals, but in extruding and being damaged. The o-ring does not need to be removed each time the pressure vessel is opened/closed, and if you are not bothering to do so, start at step 8. Otherwise:

1. if you are really worried about it, remove o-ring using o-ring extraction tool
2. check gland for large particulate matter, clean out stale o-ring grease
3. wipe off o-ring (being careful not to stretch it)
4. inspect o-ring for any tears or other discontinuities
5. If o-ring is in tact, not overly stretched, and has been used fewer than 10 cycles, it may be reused. Otherwise, get a new o-ring of the *correct* size.
6. Grease o-ring: dispense enough o-ring grease and pull it around the o-ring until it is completely covered.
7. Replace o-ring in gland
8. smear a little extra grease on the outside of o-ring and plug
9. Reseal

Initial Sealing Criterion:

When a pressure vessel is first finished and sealed, the following steps must be taken before it is considered safe for electronics:

1. Bucket testing (initial)
   If possible based on size restrictions, pressure vessel will be placed in a bucket of water. Vessel will be checked after two minutes, ten minutes, thirty minutes, and hour, and two hours. If the vessel does not leak at this time, advance to stage two of testing

2. Bucket testing (overnight)
   Submerge vessel in bucket and let it sit overnight. If vessel does not leak overnight, then it is reasonable to advance on to depth testing. The reason to do this is so that pool time is not wasted with a vessel that would have otherwise leaked.

3. Depth Testing (mechanical)
   Drop vessel down in the deepest part of the pool (12 ft) for five minutes, then fifteen, then thirty, then an hour. If it does not leak after an hour, it should be put back down for another hour. Check every hour for leaks. Once the vessel has been without leaks at depth for ten hours, it is considered safe for electronics. Included in this time needs to be an hour of changing depth tests, where the vessel is pulled up and let down multiple times to ensure that the pressure changes will not cause leaking.

4. All further pool tests:
   Before each pool test, all smaller pressure vessels (battery pods, hydrophones, etc.) need to be leak tested in a bucket for at least ten minutes. After a pressure vessel has shown not to leak after ten hours, most sealing problems will be human error in sealing. A quick bucket test will reveal many of the leaks caused by these issues. Also a vessel in a bucket will leak less quickly, which means that there is a small chance of electronics damage should a leak occur. Doing this can save hours of time fixing problems caused by leaks.

Every pool test needs to start with an “in and out” leak check. This is to check one last time that there are no fast leaks in any of the pressure vessels. This is especially important for our main electronics pressure vessel because it cannot be leak tested prior to going to the pool. In San Diego, ask the diver operating the crane to put the vehicle in then lift it back out so that you can do this same check. He may make fun of you, but that is preferable to fried electronics.

For several pool tests after a pressure vessel is “certified”, check regularly that no leaks have occurred. Even after a vehicle has been running leak-free for a while, it is not a bad idea to check every hour. If there is ever a weird electronics problem, or you loose contact with the submarine, or it shuts down, it is a good idea to check for leaks. All it takes is one loose screw on a face seal for leakage to occur and damage thousands of dollars of electronics. Better to take two minutes to check.

Leaking Protocols:

If a pressure vessel leaks, all electronics may need to be removed and the source of the leak determined as quickly as possible. Depending on the source of the leak, you may need to repeat the initial sealing criterion.

You need to use the initial sealing criterion if:

1. You are sealing a pressure vessel for the first time
2. You are sealing a pressure vessel that leaked for a structural reason

"Leaking for a structural reason" means that fixing the leak required any of the following:

- Changing connectors
- Re-epoxying
- New hull
- New sealing collars
- New endcaps
- Fixing cracks
- Different method of attachment (face seals only)

If fixing the leak required any of the following, you do not need to restart the initial sealing criterion:

- Removing a wire/other that got into the seal
- Replacing an o-ring
- Applying more o-ring grease
- Tightening down screws
- Tightening down connectors
- Cleaning the o-ring gland
- Cleaning the sealing surface

Structural leaking in Proteus, the 2006-2007 CUAUV competition vehicle. We had to start the 10 hours again after this glug leak.

If the leak is caused by a nonstructural problem, then you should document the problem and ensure that all people who routinely seal the vessel know about it. The leaking pressure vessel should also be checked regularly for several pool tests.

When Leaking Occurs:

If electronics are not in danger:

- Move slowly without disturbing water droplets.
- Try to ascertain where the leak comes from. Look for water trails and drops in any suspect areas. Places to look are at sealing interfaces and epoxied interfaces.
- Go over sealing process to try to determine anything that might have caused the leak (see troubleshooting section)
- Once you have noted which end of the pressure vessel the leak has come from if possible, open the seal slowly.
- If it is a face seal, try to lift the o-ring gland surface directly off of the sealing surface. This leaves a grease ring, which is helpful in telling if the leak was through the o-ring.
- Check all connectors to see if they are loose.
- Dry out pressure vessel entirely.

Doing 10 hours of leak testing on battery pods (with electronics removed) after they leaked during the 2007 competition in San Diego.

If electronics are in danger:

- Unseal and drain immediately, keeping water away from electronics.
- Dry out pressure vessel as much as possible.
- Remove all electronics and assess damage.
- Test as necessary to determine source of leak (see troubleshooting).

After a pressure vessel has leaked, follow instructions in leaking protocols to determine the proper course of action. Note that if there is not sufficient time to allow the pressure vessel to be tested for a full 10 hours you can make the decision to reintroduce electronics after two hours. In this case, make sure to check every fifteen minutes or half an hour for leaks until you are confident that the pressure vessel is sealing again.

A note on Lithium Polymer Batteries

Lithium Polymer batteries can react badly when wet. Because of this it is especially important to disconnect them quickly when they have been exposed to water and let them dry out. Also note that any underwater connectors you have that are being powered need to be terminated either in a cable or in a dummy plug. Not doing so can result in corroded pins.

VII. Troubleshooting Leaks:

For Face Seals

Symptom	Possible Causes	Solution
Fast Leak	No o-ring	Insert o-ring
	Popped epoxy seal	Replace hull/epoxy new hull collar
	Wire/other in seal	Remove wire/other
	Damaged o-ring	Replace o-ring
	Unseating o-ring	Tighten seal further, stabilize hull
	Uncompressed o-ring	Tighten seal further
Slow Leak/Fogging	Uncompressed o-ring	Tighten screws
	Cracked epoxy seal	Replace hull
	Damaged o-ring	Replace o-ring

For Bore Seals

Symptom	Possible Causes	Solution
Fast Leak	No o-ring	Insert o-ring
	Popped epoxy seal	Replace hull/epoxy new hull collar
	Wire/other in seal	Remove wire/other
	Damaged o-ring*	Replace o-ring
	Extruded o-ring	See below
	Uncompressed o-ring	See below
Slow Leak/Fogging	Uncompressed o-ring	See below
	Cracked epoxy seal	Replace hull
	Damaged o-ring Extruded o-ring	Replace o-ring See below

*Note: in bore seals o-ring damage can be caused because the o-ring is being extruded.

Extruded o-ring:

1. It is possible that the o-ring is merely stretched and needs to be replaced.
2. If replacing the o-ring does not work, then either the gland in the plug needs to be deepened or the face it fits into widened. Note that tolerances in the o-ring handbook are for use with thousands of PSI, so having a little more clearance will not damage the seal (see section on cutting o-ring glands). It is nice to do this before anything is anodized.

Uncompressed o-ring:
Unfortunately, there is nothing really that can be done about this in a bore seal. If there is a bevel that the o-ring is not traveling beyond, force the plug in further. Otherwise (and in most cases if this is the problem), you need new parts.