Simple Enclosure is Waterproof to 400 Metres

***David Gibson** describes a low-cost equipment housing for underwater use at depths of, potentially, up to 1000m although caving applications would normally be at a shallower depth of under 100m. Possible uses of this housing would be as part of a data-logger designed to monitor water depth (via a pressure sensor), as well as temperature, electrical conductivity and possibly turbidity and fluorescence.*

The origins of this project of mine go back 25 years but I have only recently had the opportunity to try out my ideas, as part of my work at the University of Exeter's Camborne School of Mines.

Waterproof Housings

Most off-the-shelf waterproof boxes are not suitable for total immersion, and the IP68 rating, commonly applied, only covers protection at modest depths (perhaps up to 3m). The reason why most 'domestic' waterproof boxes will not withstand immersion is because the box flexes under pressure and the integrity of the seal is not maintained. I first considered this problem 25 years ago, and wrote a brief note in CREG Journal 12, in June 1993. In my note, I reported that the professional advice from submarine engineers was to use a cylindrical housing with plugged ends using O-ring shaft seals. One salient point is that, because such an enclosure is symmetrical, it is easier to design and model as the stresses are more predictable – and it is stronger and more reliable, of course. It has taken me 25 years to get around to experimenting with such an enclosure, but I can now report some results.

Of course, enclosures that follow the above principle are now available commercially – see, for example, ref. [1] and [2] – but I am interested in a low-cost option that might be suitable for caving projects.

Penetrators

The weak points in any waterproof housing are the connectors to bring electrical signals in and out. Waterproof connectors to use at significant water depths – or 'penetrators', as they are called – can be extremely expensive. The project I envisaged, 25 years ago, was a waterproof data-logger for which the problem of the penetrators was circumvented by simply not having any. The logger would record only those parameters that it could measure internally, which might limit it to temperature, two-terminal conductivity (via the metal end caps), and water pressure. Pressure is a useful parameter to record in a submerged data logger because it is related to water depth, which is of interest to cave hydrologists – see Nigel Ball's article on the unusual flooding characteristics of Speedwell Cavern [3; Ball, 2013], and *Figure 1* below.

Sensors

Water pressure is easily measured using a sensor designed to fit in the wall of the enclosure. The products available when I first considered this project contained only a high-precision strain gauge, leaving the user to design the signal-conditioning circuitry. However, modern devices include an embedded digital signal processing core for the compensation and normalization of the signal, which is digitised on-chip, making the parts easy to use.

Figure 2 shows a typical example from Keller-Druck [4]. Also see *Table 1*, on the next page.

Materials

Materials for submarine enclosures can be expensive. Anodised aluminium and stainless steel may not function as well as titanium and specialised ceramics.

Some housings achieve their strength by being oil or gel-filled, with a means of equalising the pressure using a flexible membrane. Although electrically inert oils and gels are available for this purpose, there is the question of whether this simply transfers the problem to another part of the equipment – e.g. the battery.

Figure 2 – A pressure sensor for use at water pressures of up to 1000 bar

Design of the Prototype

The intention of the present project was to design a low-cost enclosure for a set of data loggers that could be placed throughout a disused mineshaft (up to 1500m deep) to log data as the shaft slowly flooded. Caving applications to monitor water depth would not require such a stringent depth specification.

It was decided to use a plug-end cylinder made from a transparent plastic, with aluminium plug ends. A metal

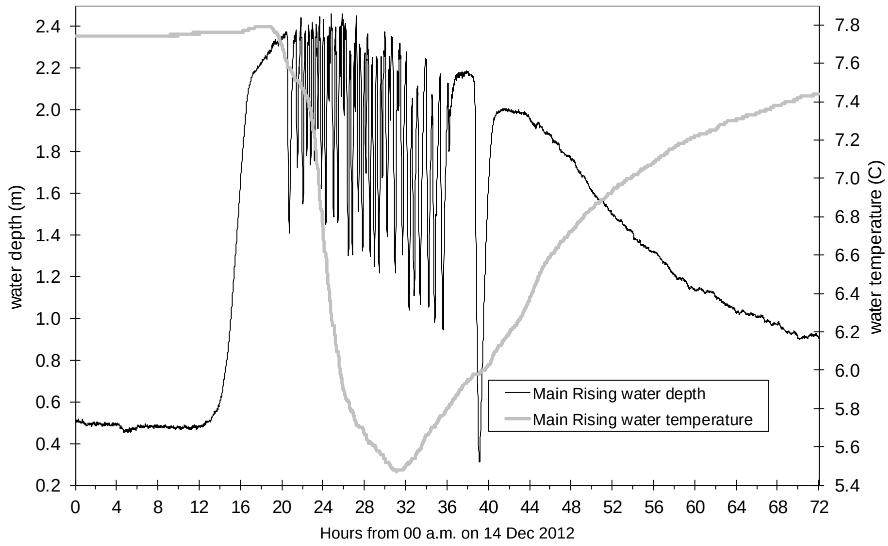

Figure 1 – Water depth and temperature at Main Rising, Speedwell Cavern
Showing the unusual repeated pulsing of the water flow. See [Ball, 2013]

enclosure would be more rugged, but it was considered that, during development, it would be useful to view the status LEDs on the circuit board. Additionally, there is the possibility that parameters such as fluorescence and turbidity could be measured without the need for penetrators.

We initially considered two materials, a clear polycarbonate and an acrylic material (PMMA; Perspex). The salient difference was that the polycarbonate housing would be a bespoke, machined part whereas the acrylic would be 'off-the-shelf'. We decided to use the off-the-shelf part because it was considered that machining operations could introduce micro-fractures that would reduce the performance of the material.

The yield stress for both materials suggested that they would be suitable for prototypes, although using steel or aluminium alloy would have raised the yield strength by some 3.5 to 6 times. However, yield stress might not be the crucial factor for maintaining the integrity of the housing, because it is the flexing of the walls that could disrupt the O-ring seal.

Theoretical calculations

It is well-established that, of the three components of stress in a cylinder wall – circumferential (or hoop), radial and axial – the most significant component for a *thin-walled* cylinder is the circumferential stress σ_φ, which is given by

$$\sigma_\varphi = P\,r\,/\,t \qquad (1)$$

where P is the differential pressure, r is the radius of the tube and t is the wall thickness with $t << r$. Thus, if $r = 20$mm and $t = 2$mm, and the yield strength of the material is (say) 70MPa, for Perspex, this suggests that the yield pressure will be around 7MPa or around 70 bar.

That is the yield pressure for a cylinder with a positive internal pressure. In our situation, the internal pressure is negative and the yield stress is a compression. A thin-walled metal cylinder would be prone to buckling in compression and the need to avoid this suggests a thick wall is needed, for which the above thin-wall approximation is not the correct model. To further put this in context, the axial stress σ_z is

$$\sigma_z = Pr\,/\,2t \qquad (2)$$

which is derived simply from the end force (pressure × area) divided by the cross-sectional area of the wall. Instead of pressure, we can imagine a mass M placed on top of a vertical cylinder, which gives rise to a force Mg. The yield stress σ is now

$$\sigma = Mg\,/\,2\pi rt \qquad (3)$$

Description	PA-7LD / 200 bar / 10-0722-100
Keller product number	100722.0105
Pressure range	0…200 bar
Supply	1.8…3.6V
Output	I^2C
Electrical connection	7cm wire
Compensated temperature range	0…50ºC
Total error band (TEB)	0.5%FS
Linearity BSL fit	0.15%FS

Table 1 – Specification of the Pressure Sensor from Keller-Druck [4]

Length	o.d.	Wall Thickness	Predicted Failure (simulation)	Predicted Failure (thin-wall formula)
150mm	40mm	2mm	67 bar	70 bar
150mm	40mm	3mm	98 bar	105 bar
150mm	50mm	2mm	54 bar	56 bar

Table 2 – Results of simulations for off-the-shelf acrylic tube (UTS 70 MPa)

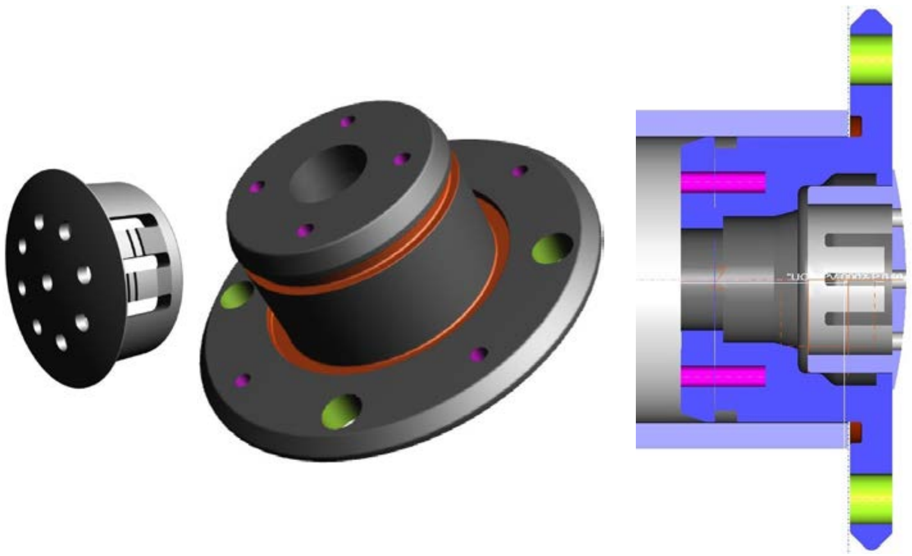

Figure 3 – Pressure housing: 3D CAD drawings of end cap
1: Vented plug. 2: End cap. 3: Cross-section of end cap and plug

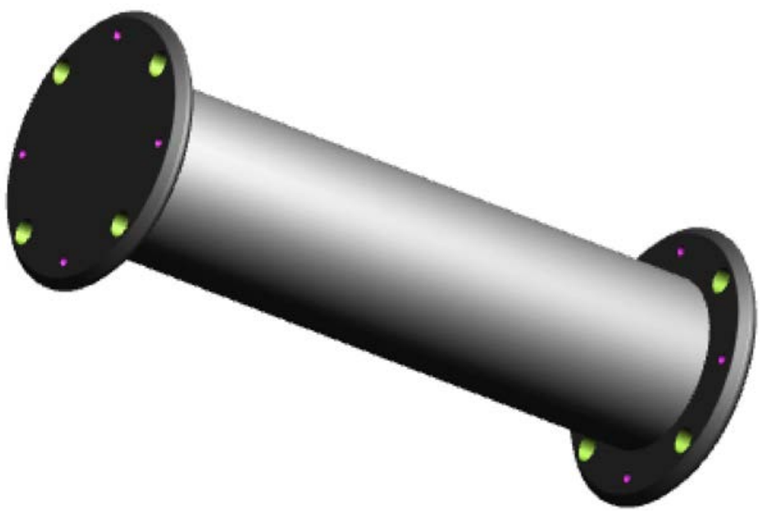

Figure 4 – Pressure housing: 3D CAD drawing of enclosure

which indicates, with the above figures, a mass of about 1,800kg. This seems to be rather a large load to be supported by such a small cylinder and so the validity of the calculation is therefore in doubt.

Finite Element Analysis

An FEA was undertaken to confirm the above results. Surprisingly, there was quite a good agreement to the simple calculation given above. However, one limitation of our brief analysis was that it only allowed us to predict the pressure at which the ultimate tensile strength of a given material was reached. That is, it did not predict the failure mode, but assumed that the failure would be catastrophic.

As noted above, with a bespoke fabricated assembly, the failure mode will likely be generated by a localised (and unpredictable) flaw in the material surface. There are less likely to be flaws generated in a manufactured polished tube, and therefore it was considered that this might be the better approach to use for this design. This was our reason for using off-the-shelf acrylic tube.

The results of the FEA are shown in *Table 2*. For the thinnest walls (2mm) the FEA shows good agreement with the theoretical thin-wall calculations but this suggests that the simulation has not fully addressed the problem of buckling and that we could expect failure at a lower pressure than the simulation suggests. Ordinarily, FEA would be used to indicate a failure mode for a given assembly, and then a safety factor of, say, 4 times would be applied to ensure the assembly did not undertake catastrophic failure.

Design of Housing

As a result of the simulations, it was decided to use an off-the-shelf acrylic tube 150mm in length, with a 40mm O.D. and a wall thickness of 3mm. The failure was predicted to be at 98 bar with a zero safety factor. The end caps were machined in aluminium and hard-anodized. Two O-ring seals were used – a face seal, against the plate of the end cap and a transverse seal against the wall of the tube. A number of holes were pre-drilled into the metal to allow for anchoring points.

One of the end caps was machined to fit the pressure sensor. To protect the delicate sensor from damage, a commercially-available vented plug was fitted, similar to the Multicomp and Heyco products available at, e.g., **uk.farnell.com**. A selection of the 3D CAD drawings is shown in *Figure 3* and *Figure 4* (see previous page).

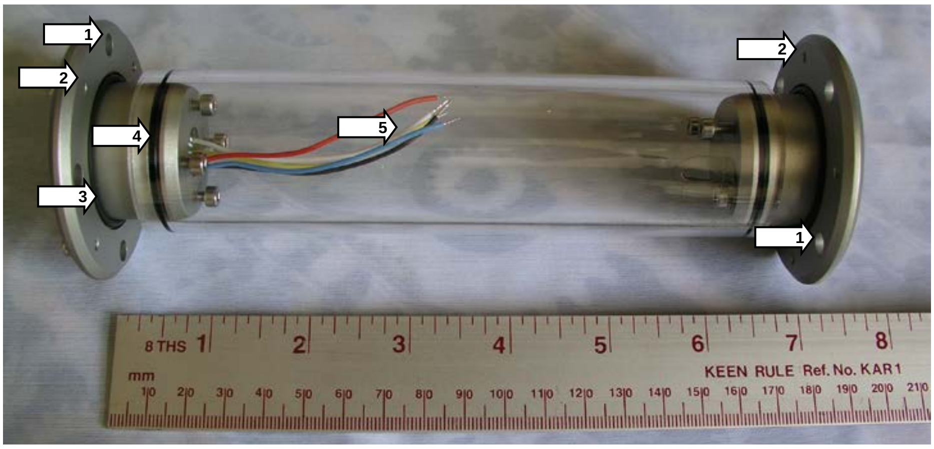

Figure 5 – Pressure housing: manufactured prototype
1: *holes (x4) for M5 threaded rod that clamps assembly together.*
2: *general-purpose holes (x4) for M3 bolts.*
3: *O-ring end seal.* ***4:*** *O-ring circumferential seal.* ***5:*** *wires from pressure sensor.*

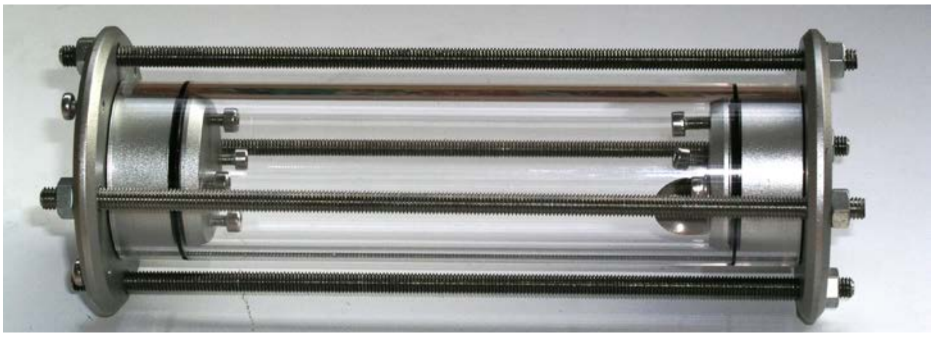

Figure 6 – Pressure housing: retaining assembly
Showing the four M5 threaded rods which clamp the assembly together

Figure 7 – Pressure housing: packaged for lowering into a mine shaft

Figure 8 – Flooded shaft at South Crofty mine, Cornwall
Showing the prototype being lowered into the water

Figure 5 (previous page) shows a photo of the prototype enclosure. For this photo, the pressure sensor has been fitted, and its flying leads are visible, but there is no circuit board in the enclosure. Note that the transparent housing allows the O-ring seal to be inspected for integrity. The O-ring seal was a slight concern because the acrylic tube could not be chamfered to aid the fitting of the end caps as this might have compromised its integrity by introducing micro-fractures.

Figure 6 shows the four threaded rods which hold the assembly together. These are redundant once the assembly is underwater as the water pressure alone is sufficient to hold the end caps on. However, on the surface they are required to counteract the back-pressure that arises when the end caps are pushed home.

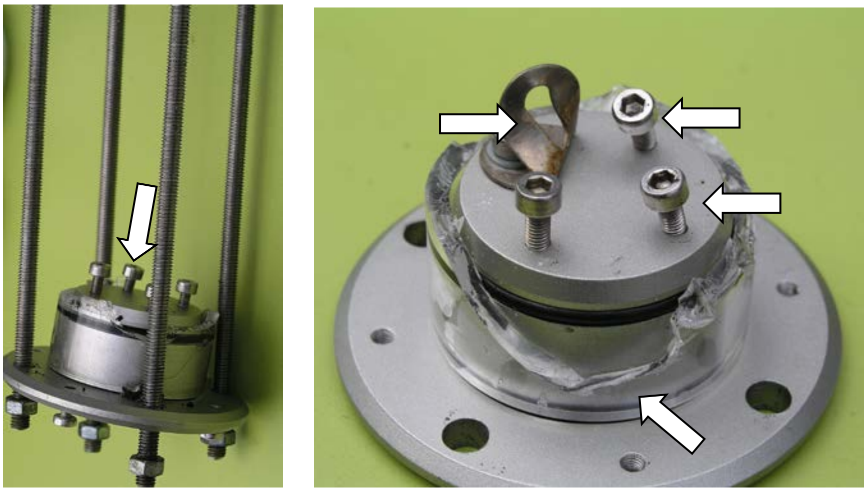

Figure 9 – Damaged pressure housing, after 600 m depth test
Arrows indicate the places where the enclosure suffered damage during the 700 m pressure test

Underwater Testing

For testing, the enclosure (without any electronics inside) was loosely held inside a length of 70mm plastic drainpipe for protection and was lowered into a flooded mineshaft at South Crofty mine in Cornwall on a thin polypropylene rope. See *Figure 7* and *Figure 8* on the previous page. The shaft was believed to be around 900m deep, although it was known that there was debris in the shaft in the lower sections.

The device was weighted, and lowered in three tests, to 100m, 400m and 700m of water depth. The first two tests showed no ingress of water but, on retrieving the housing from the third test it was found to have failed.

On closer inspection, the plastic drainpipe, intended to protect the enclosure from damage, was found to be damaged, with a number of longitudinal fractures and it was only held together by the gaffer tape that had been wrapped around it. The enclosure itself had shattered into small pieces and some of the M3 mounting bolts and a small bracket inside the enclosure (unused for this test) had been considerably bent. See *Figure 9* (right). It was considered that the reason for the failure may have been as follows.

1. For the third test, the M6 bolts across the plastic drainpipe, that were intended to hold the enclosure in place, may have been over-tightened, so that the drainpipe gripped the flange of the enclosure's metal end cap too tightly.
2. As the unit was lowered, by hand, an obstruction was detected (by a change in the weight on the rope) at about 600m. On raising the unit, it was necessary to tug sharply to free it. Inspecting the recovered unit showed that the top of the plastic drainpipe was filled with large fragments of rusted iron, as if it had scraped past something.
3. If the enclosure was under force as it was dragged upward past the obstruction, it may have twisted slightly, possibly over-stressing the acrylic or perhaps momentarily flexing the O-ring seal. Alternatively, it could just be that the acrylic was over-stressed by the water pressure alone.
4. Either way, the inrush of water at 60 bar (6MPa) must be responsible for the observed damage – bending the screws and bracket, shattering the acrylic and shredding the drainpipe. The process may well have been similar to that which occurs when a balloon bursts.
5. 600m depth is 60 atmospheres and 6MPa. The M3 bolts presented an area of (say) 3mm × 10mm to the sideways pressure, which corresponds to a force of 180N or 18kg, so it is not surprising that the bolts and bracket were bent so noticeably.

Concluding Remarks

Given that the enclosure was simulated to fail at 98 bar with a suggested 4× safety factor, it was expected to withstand 250m of water, which it did. The failure mode may well have been similar to that of a pressurised balloon – the enclosure probably 'burst' when it was stressed by tugging it against an obstruction.

Better protection against external stresses and a thicker wall to the enclosure should provide the necessary protection. It should be noted, though, that at this stage we have not performed a long-term leak test. Also, we have not evaluated the long-term integrity of the O-ring seals in a minewater environment, which is usually quite corrosive.

The pressure sensor required a high-precision hole in the end cap. This, and the fact that the end caps were hard-anodised, meant that the prototype parts were not cheap. One of the aims of this work was to produce a low-cost housing, but we consider that the general concept of a plug-end cylinder being potentially low-cost is still valid.

Uses in Caving

For caving applications, at much shallower depth, it should be possible to 3D-print an end cap, which would keep the cost down.

The pressure sensor we used was a high-performance part designed for extreme depth, but a lower specification part would be cheaper and would not require such a high precision mounting hole.

Acknowledgements

Camborne School of Mines thanks Keith Russ at South Crofty mine for arranging access to the flooded mine shaft. The prototypes were manufactured by Glenelg Design Ltd.

This work was funded, in part, by the Research Fund for Coal and Steel of the European Community.

References

1. **omniinstruments.co.uk/subsea-aluminium-housings-for-water-depths-to-300-metres.html**
2. **impactsubsea.co.uk/wp-content/uploads/2016/04/ISP1-Datasheet.pdf**
3. Ball, Nigel. (2013). *The Flooding Characteristics of Speedwell Cavern*. Speleology **19**, pp38-39. Available at **bcra.org.uk/sp/?j=19**
4. **keller-druck.ch/home_e/paprod_e/hm_transm_e.asp**

Ω