THE FOUR TENETS OF PRESSURE VESSEL DESIGN

Abstract

This article discusses the four tenets of designing pressure vessels: Corrosion Management, Hydraulic Performance, Media Optimization, and Maintenance and Operations and its relation to optimizing PFAS removal. Enlisting strong specifications, computational fluid dynamics software, and piloting, engineers can impact on pressure vessel lifespan, cost of ownership, and ease of operations. Leveraging a career in activated carbon vessel design, the author explains pressure vessel design steps that ensure the least complex and most cost-effective outcome.

Keywords: PFAS, pressurized vessels, contaminants of emerging concern, design, GAC, Ion exchange.

Engineers pride themselves on the performance of their design once the concrete has been poured and the cranes leave the site. So, when utility customers report premature failures and underperformance, engineers are left questioning the cause. Their team spent hours perfecting the sizing, media type, and redundancy needed to serve their client for years, only for it to fail before anyone anticipated.

As state and federal drinking water agencies pass regulations for contaminants of emerging concern like PFAS with increasing frequency, engineers across the US will be relied on to design the necessary solutions to remove them. Pressurized vessels have served New England communities for decades to combat a long list of water contaminants. But system failures and expensive operations costs can frustrate water providers aiming to distribute clean, affordable water to their ratepayers.

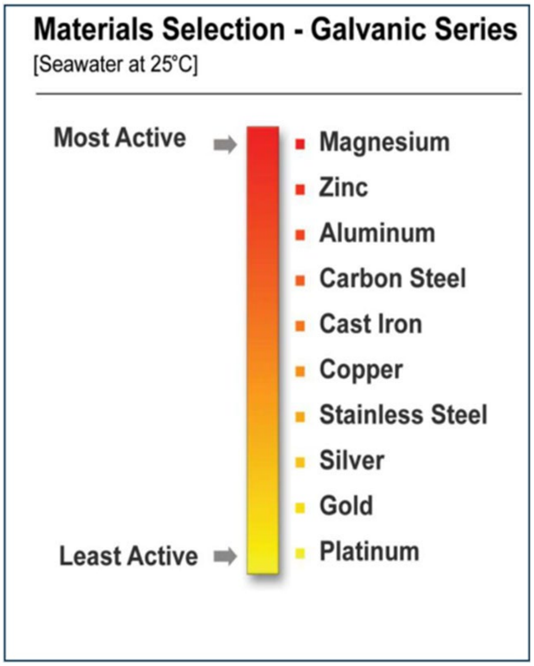
It all starts with a quality design. Equipped with the four tenets of pressure vessel design, water infrastructure engineers can optimize pressure vessel treatment performance while ensuring a maximized life expectancy with the lowest cost of ownership for their customers.

Corrosion Management

Water. Air. Sunlight. The environment that pressure vessels live in makes corrosion inevitable. However, the design phase can lay the foundation for anticipating and deterring premature vessel corrosion. Engineers can ensure their designs have a long life with minimal operations costs by considering vessel materials, writing strong coatings specs, and making maintenance accessible for operators, among other considerations.

Materials

When selecting vessel materials, the Galvanic Series can serve as a simple guide to minimize a pressure vessel's corrosion potential. Anodic and cathodic metals used to build pressure vessels will naturally interact as raw water serves as a medium between the two, setting the stage for a chemical reaction. Accounting for this, a critical aspect of corrosion control is choosing materials that are not widely separated within the galvanic series that may foster a speedier rate of degradation of the vessel's anodic metal.



In addition to the material selection, coating these metals appropriately is another important piece of corrosion control. During the design phase, some vessel specifications exclusively call for the coating of the anodic member, as this is the electron donor that erodes. However, NACE (now AMPP) recommends coating both cathodic and anodic metals to reduce the interaction between them[1].

Simply coating a vessel is not enough to prepare for corrosion either. In fact, 70% of pressure vessel coating failures are due to inadequate surface preparation[2]. By borrowing specifications from the Society of Protective Coatings, SSPC SP-5 or NACE Standard RP0178-2007, and coating manufacturer recommendations engineers can ensure that vessel materials are free of oils, dust, and rust before being coated, installed, and exposed to the elements.

Welding specifications can also lay critical groundwork for long term life and reduced corrosion rates, such as NACE RO0178, which requires welds and sharp edges be ground down to avoid crevices.

Design

The physical design of a vessel can also impact rates of corrosion and lifespan. After deciding on materials, engineers must gather and analyze water quality data such as inlet water temperature, flowrates, hydraulic loading, required pressure, and general water chemistry considerations.

Pressure vessel design is significantly impacted by the geometry of the underdrain design. A proper underdrain design can prevent electrolyte build up which corrodes vessel outlets. In correlation with the welding specifications, avoiding creating any unintentional crevices within the vessel will prevent eddies and stagnant water and media that wear coatings and vessel materials. Finally, designs should facilitate accessibility for operators and technicians to access the inside of vessels and perform timely maintenance, such as periodic media exchanges and recoating.

Hydraulic Performance

When designing pressure vessels, it is important to categorize them into three regions:

- **Overdrain** - Where water enters the system and is distributed onto the media bed.
- **Media Bed** - A resin or carbon-based media that interacts with water on a molecular level to remove contaminants, ideally in plug flow and isotropic distribution.
- **Underdrain** – Nozzles or slotted pipe that separates treated water from media.

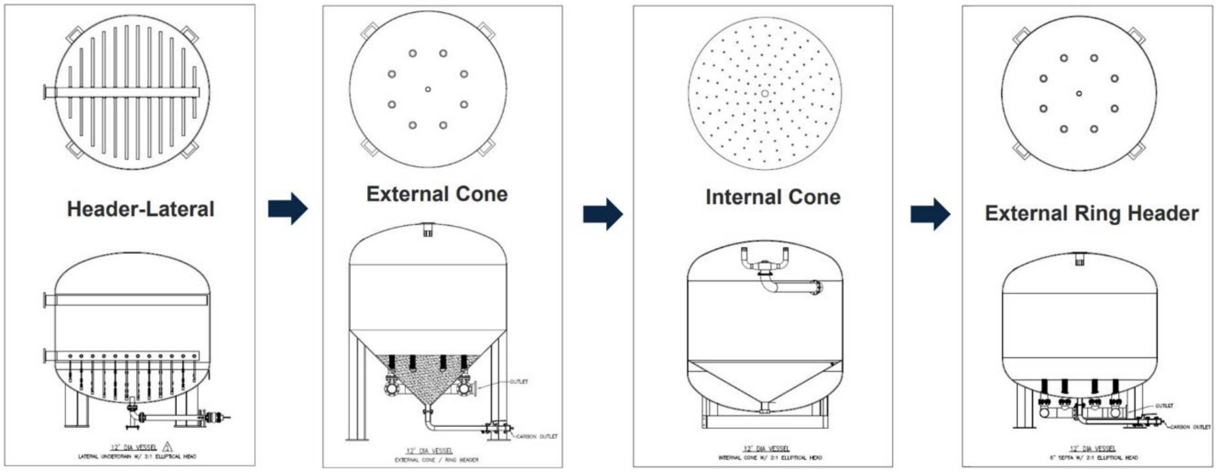
The coordinated sizing and geometry of these three regions can dictate the long-term performance of a pressure vessel and have considerable effects on corrosion rates, lifespan, and operational cost. Each region must work in harmony to create a plug flow within the media, the ideal hydraulic condition for pressure vessel treatment.

The Three Regions

Overdrain design establishes the pressure differential within the system and offers different distribution patterns. Based on the pressure differential required, industry standard designs such as Inlet Diffusers Header-Lateral Distributors, Four-point Nozzles distribute influent onto the media bed.

There are four well established underdrain designs that play an equal and opposite role to the overdrain, maintaining appropriate outflow rates, plug flow, and the proper pressure differentials within the vessel.

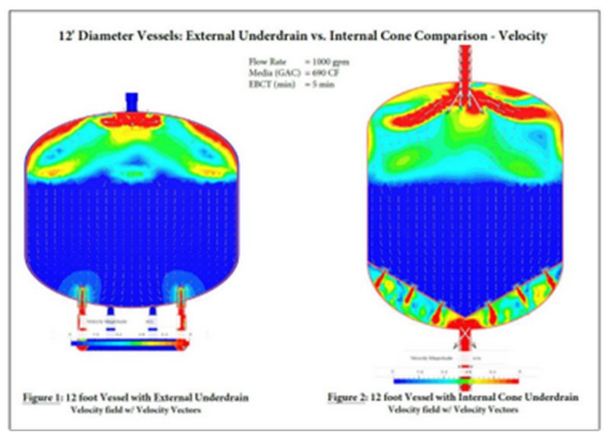
- **Header-lateral** – Typical for smaller vessels, this design employs a horizontal drainage pipe with laterals to drain treated water to the outlet.
- **External Cone** – Also common in smaller vessels, this design uses a circular pattern of nozzles and screens.
- **Internal Cone** – More typical in larger vessels, this underdrain is welded inside the unit. Its design is similar to a colander.
- **External Ring Header** – The latest evolution of underdrain design, the external ring header uses nozzles and screens and fits flush with the vessel.



Optimizing the water flow between these three regions while also optimizing the media will save costs over the operational life of the vessel. Taking the relationship between these three regions into account during the design phase pays dividends in saved energy, lower maintenance time and expenses, and optimized media use. Minimizing head loss and achieving plug flow are the keys for vessel design, which can be aided by modern modeling tools.

Computation Fluid Dynamics

With the proper software, design engineers can take the parameters discussed here to experiment with and identify a design that will maintain plug flow within a vessel. Computation Fluid Dynamics (CFD) software provides a model of internal velocity and pressure distributions of fully developed flows, which is helpful for internal flows that can't be viewed. CFD models can inform sizing and validate the individual designs of the three vessel regions.



Media Optimization

CFDs continue to play an important role in design when optimizing media. The velocity maps that CFDs provide are a valuable tool to select the best overdrain and underdrain for the job, which can have long lasting effects on mass transfer zone performance and achieving plug flow. Pressure vessels often contain Granular Activated Carbon (GAC), and for good reason; it's a universal water purifier that removes countless water contaminants. However, in the face of contaminants of emerging concern such as PFAS, other media may be better suited to secure long-term lifespan, manageable maintenance costs, and treatment performance results of a water utility's unique situation.

Suggested Equation: EBCT (min) = Carbon Vol. (ft^3)/ Flow Rate (ft^3/min)

Granular Activated Carbon (GAC)

GAC is produced from various raw materials and manufacturing processes. Common carbon sources, such as coconut shell, bituminous, sub-bituminous, and lignite carbon, require different processing. Raw materials such as coconut shell, sub bituminous and lignite coals do not require an agglomeration process due to the inherent porosity of the starting material.

Carbon's ability to adsorb the most water contaminants has made it a long-established choice for water treatment. GAC vessels operate at hydraulic loading rates between two and ten gallons per minute per square foot (gpm/ft^2) and typically 10 minutes of empty bed contact time (EBCT). The density of the activated carbon must be taken into careful consideration since in some cases, bituminous coal-based products can be up to 20% more dense than sub-bituminous and lignite coal-based products. It has been shown that sub-bituminous and lignite coal-based products can treat equal volumes of water at identical empty bed contact times, meaning the carbon use rate in lbs of GAC/1000 gallons of water is less for the sub-bituminous and lignite-based carbons.

Competitive adsorption from other organic compounds in the feed water can reduce the adsorption capacity for targeted compounds such as PFAS. Feed water containing high total organic carbon (TOC) or other competing contaminants may shorten the life of the GAC media bed.

Ion Exchange (IX)

IX tends to cost more per pound but can target specific contaminants like PFOA and PFOS. They treat PFAS at an EBCT of 2-3 minutes, withstand higher hydraulic loading rates, between 6-18 gpm/ft^2. While IX can more selectively treat contaminants than GAC, competing anion contaminants such as SO4, NO3, and TOC must be accounted for in sizing and predicting media bed lifespan.

Proprietary Media

PFAS is a complex family of chemicals that has inspired alternate media development. Proprietary media such as CETCO's Fluoro-Sorb6 offering a two-minute EBCT and hydraulic loading rate of up to 14 gpm/ft^2. Performance testing shows that this medium matches the results of IX and is effective against both long and short chain PFAS. Media lifespan is fully dictated by PFAS concentrations. No matter which media is right for the job, the ability to access, remove, and replace spent media for inspection, regeneration, or incineration is vital to facilitating long-term operations and maintenance by staff for decades to come.

Long-term Operation & Maintenance

Pressure vessel design doesn't end after selecting media. The final tenet of pressure vessel design considers where your final product will live and how it will be operated and maintained. The design choices made earlier in the process can dictate the standard operating procedures required of utilities once they take ownership.

Of particular note are the underdrains.

- **Header-Lateral** - The internal structure of this design challenges lining can cause corrosion. Media must be removed from the vessel for any underdrain maintenance and requires confined space protocol when being maintained.
- **External Cone** - Allows for simpler media exchange, with its conical shape pushing media towards the center. There is no vessel entry required for working on its nozzles and no confined space protocol is required for maintenance.
- **Internal Cone** - Welded inside of the vessel, this cone design increases the height of the vessel. Because of its shape and welding seams, this design comes with lining challenges and can be prone to corrosion.
- **External Ring Header** - This design allows for shorter heights, which is advantageous when installing in existing buildings. It features one homogenous lining throughout the vessel to avoid corrosive crevices, and it doesn't require carbon removal for maintenance and repair or confined space entry.

Description	External Ring Header	Internal Cone	Header Lateral
NACE Standard #RP0178-2007 Compliant	✓	X	✓
Design Mitigates Risk of Corrosion	✓	X	✓
One Homogenous Lining	✓	X	✓
Underdrain Fully Pressure Rated to the Vessel	✓	X	✓
Media Optimized Design Volume Beneath Top Nozzle	✓	X	X
Optimizes Pressure Drop & Pumping Costs	✓	X	X
Prevents Confined Space entry	✓	X	X

Design Considerations

When vessel professionals discuss simpler designs, they are typically referring to ease of inspection during service events. Especially when using media that needs reactivation like GAC, accessibility and lack of confined space protocol makes upkeep uncomplicated and less of a hassle for operators.

These systems often operate inside a building, so designing them with height in mind can have considerable effects on a facility's broader operational costs. The annual electric costs related to HVAC, heating and cooling, and pumping water to the overdrain are all directly affected by vessel height.

The use of expansion joints when constructing pressure vessels can allow for on-site assembly where needed. However, expansion joint materials, such as EPDM Rubber and Neoprene, withstand much lower pressures than steel and are degraded by UV over time.

The final design parameter to consider is backwashing. Media like GAC and Fluoro-Sorb require backwashing to stratify the media and remove fine particles. Backwashing capabilities require a larger volume vessel to make space for the process.

PFAS Removal in the Field

When designing pressure vessels to remove PFAS, there are a host of factors that will affect the design. When choosing media, engineers must consider the types and concentrations of PFAS compounds, the presence of competing contaminants, and associated plant upgrades required prior to the pressure vessels and media. With the four tenets of pressure vessel design in hand, engineers can rest assured their design will perform well for water providers and protect public health.

Conclusion

As new federal and state PFAS regulations change the landscape of water and wastewater treatment, consulting engineers will continue to see an uptick in treatment projects to remove and destroy these chemicals. Pressure vessels have shown great results in the removal of PFAS, due to their media variability, throughput, and cost of ownership.

Following the four tenets of pressure vessel design, engineers can ensure that they build the least complex system with the lowest cost of ownership to prevent those late-night calls from clients dealing with failing equipment after the project has been completed. The order of operations presented here is gleaned from hundreds of years of collective experience in designing, constructing, and operating these systems globally.

Consulting engineering comes with variety, so if pressure vessels are new to you, these tenets can guide you to the best solution for your project. It's also recommended to work with a technology provider early in the process, to leverage their experience and augment design quality.

References

[1] NACE International, 2000. NACE Publication 80200/SSPC-TR 4-2000, Preparation of Protective Coating Specifications for Atmospheric Service.

[2] Ibid.

About the Author

Richard (Bo) Botteicher, PE is the Vice President of Execution at AqueoUS Vets. With extensive experience in engineering, operations, project management, sales and marketing, and P&L experience that has worked to build products, services, and brands in the water and wastewater markets of North America over the last 20+ years.