FRP Membrane Vessel Fabrication and Safety in a Growing Market

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Abstract

The global demand for seawater desalination using reverse osmosis is pushing the membrane pressure vessel industry to its limits of capacity. Current peaks in demand for filament-wound fiber-reinforced plastic (FWFRP) vessels has resulted in a rapid increase in production among existing suppliers and has drawn new and inexperienced suppliers into the market. The rush has lead to short-cuts, oversights and mistakes in vessel design and fabrication, subjecting users to unnecessary risk. In years past, strict adherence to pressure vessel codes and standards, as well as independent third-party inspectors, helped keep the industry safe. Now it appears that the hard lessons of the past have been forgotten and membrane pressure vessels are treated simply as commodities conveying little if any risk. In fact, the fabrication of FWFRP membrane housings involves careful control of many critical variables in order to assure a long, safe period of usefulness. A history of vessel failures, failures that include catastrophic releases of end closures, has put the industry on notice that flawed FWFRP membrane vessels can have life threatening defects. The high standard of care afforded by compliance with the American Society of Mechanical Engineers (ASME)_Boiler and Pressure Vessel Code has been demonstrated as necessary and prudent in the membrane industry. A retreat from this standard could lead to charges of negligence in protecting the public from foreseeable dangers.

The authors present an overview of FRP membrane vessel design, fabrication, testing and inspection processes. Key process variables and their potential affect on vessel safety and longevity are considered. The role and value of International standards and third-party certification is reviewed.

I. THE INTRODUCTION OF FRP MATERIAL TO DESALINATION

In the early years of the commercialization of membrane technology, the early 1970s, the focus of development was on applying membranes in competition with conventional separations technologies (thermal) and on improving the membrane element itself. Membrane pressure vessels or housings were simple assemblies of coated carbon steel, or stainless steel pipe with end closures made with grooved pipe couplings. Significant problems with corrosion, and the occasional release of an end closure, led to a more rigorous approach to membrane housing design and to the search for materials that were inherently corrosion resistant.

The membrane industry found an economical solution in filament-wound fiber-reinforced plastic (FWFRP) pipe. FWFRP pipe has exceptional strength and corrosion resistance due to the favorable orientation of continuous strands of high-strength glass-fiber reinforcement bonded together in a matrix of corrosion resistant polymer resin. Furthermore, filament-wound pipe or tubing is superior to commercial steel pipe for use in membrane housings because it has a smooth and truly round interior surface as a consequence of being formed on precision-ground mandrel tooling.

At the time, FWFRP pipe was well established in the chemical and process industries with more than 20 years of successful application. The tubular body wall of a membrane housing was, and is wound in the same manner as pipe, i.e. the continuous fiber reinforcement is wound at a precise angle to align with the resultant of the biaxial stress in the wall. The closure at each end of the tubular body however, presented a serious technical challenge to the FWFRP industry.

The challenge was that directly outboard of the fluid-tight seal at each end of the vessel, principal stress in the wall is oriented axially but the orientation of the reinforcing fiber is predominantly circumferential. This mismatch in alignment was fundamentally wrong for filament-wound structures. The experienced FWFRP pipe suppliers felt that because “full-bore” access to the vessel precluded continuous winding over at least a portion of the end closures, filament-winding was not an appropriate method of manufacture. Established FWFRP pipe companies declined to participate because they felt that catastrophic end failure was likely over time.

The companies that did enter the membrane housing market in the early 1970s were specialty filament winders who made parts to customer’s specifications. These contract manufacturers required the membrane suppliers to design their own housings and thereby accept the design liability as well. This led to distinctively different methods to retain the end closure. Some used adhesive bonded FRP collars (National Vulcanized Fibre [NVF] for Fluid Systems). Others designed housings that were machined on the outside diameter and used large “clam-shell” clamps to retain the head (Spaulding for Hydranautics). Yet others cut a retaining ring groove into the inside diameter of a thickened section of the pipe (Amalga, NVF and Spaulding for DuPont). Regardless of the type of end closure, it was up to each membrane supplier to complete their own risk assessment and then establish margins of safety for their designs.

1.1 Filament Winding—a Complex Process that Requires Discipline and Total Quality Control

Filament winding is a unique fabrication process that incorporates continuous strands of high-tensile-strength fiber into a composite material that has exceptional, but highly-oriented strength. The strength in any given direction depends not only on the orientation of the fiber but also on a number of other variables of manufacture. The important point to remember is that for all its potential strength, a filament wound composite is dependent on, and very sensitive to, controlling these variables after a successful design has been obtained

In the case of a membrane housing, a lapse in control in any of a number of these critical variables can have life threatening consequences if the technically challenging end closure is affected. Unfortunately, a housing that has a fatal defect can appear to be identical to a good housing. The only way to assure that each and every article of manufacture is the equal of an approved prototype is to rigorously monitor and control process variables as each part is being made. Some of the variables that must be maintained consistent from part to part are as follows:

- The mechanical properties and consistency of the base materials; e.g. reinforcing fibers, fiber finish, thermoset resin and resin hardener; as certified by the manufacturer and verified by the fabricator.
- Precise control of resin mixing, temperature and viscosity
- Appropriate fiber tension, moisture content and temperature
- Uniform fiber wet-out
- Uniform width and density of the wet band of reinforcing fiber
- The angle of the band relative to the mandrel axis
- The density of the fiber band
- Precise placement of the fiber band, not only in the tubular wall but also at the critical end closures (a step that requires many gear changes or a computer-controlled winding machine)
- The exact combination of helical patterns, winding angles, circumferential patterns and hand-placed reinforcement material used to create a composite free of gaps, overlaps and other discontinuities
- The percentage of fiber in the composite
- The degree of curing of the composite

Although housing design was nominally the responsibility of the membrane supplier, the practical design as well as the all important control of the variables of fabrication process was in the hands of the filament winding supplier. Development of the processes involved a considerable amount of trial and error in processing until a “design” was shown to be capable of withstanding the operating conditions.

1.2 The Importance of Fiber Orientation

In complex filament winding such as is done on current generation membrane housings, a four-axis computer controlled machine lays down successive bands of impregnated glass roving over a rotating mandrel. Winding is done in balanced helical layers where each layer typically requires several passes of the horizontal carriage to form one complete layer. Within each helical layer the angle of the continuous glass fiber angle is approximately 54 ¾ degrees. Precise placement of fiber is critical to the strength of the composite. Depending upon the design and pressure rating, multiple helical layers are wound until the required thickness is achieved. During winding, the angle of the band relative to the mandrel axis is adjusted to ensure closure of each layer so that there are no gaps or overlaps which drastically reduce strength.

Properly fabricated a filament wound membrane housing takes full advantage of the strength of the fiber reinforcement. However the structure is much weaker when retaining ring or collar grooves are cut in the composite to make the end closure; wound-in grooves are much preferred. The strength of the composite in cut groove areas is limited to the strength of the resin itself.

II. FRP FAILURES AND THE NEED FOR A STANDARD

Although there were scattered failures prior to 1977, the more notable failures of FWFRP vessels and vessel components occurred at the Charlotte Harbor facility in Florida, the Island Water Facility in the Florida Keys and in Malta where 27 housings failed during the start-up of the system. The catastrophic failures of vessels at Orange County Water District's (OCWD's) Water Factory 21, however, were pivotal in creating awareness of the consequence of catastrophic end closure failure. The five million gallon per day system was installed in the late 1970s by Fluid Systems and was the first large municipal use of 8-Inch-diameter FWFRP vessels which had adhesive-bonded FWFRP collars.

The first OCWD failure, which occurred in early 1978, released the end closure from one vessel. The end closure went through a concrete-block wall into an acid-injection room only 15 minutes after an elementary school had toured the membrane facility. While Fluid Systems and their housing supplier tried to quickly determine if the OCWD failure was an isolated issue, a second vessel failed in the same exact manner as the first. The second failure ruined equipment located nearly 20-feet away as well as three membrane elements that were also ejected.

While the first failure caused doubt about the consistency of quality of the housings, the second failure made it obvious that the failures could not be viewed as isolated incidents. OCWD determined that, for the sake of pubic safety, they could not wait for a solution and that the system could not be operated until either all vessels in the system were replaced or until the threat of catastrophic failure had been mitigated.

To preclude the release of more end closures, each rack was fitted with a metal cage at each end held together with tie-rods that ran from end to end. Similar structures were also placed around other systems that used the adhesive-bonded-collar vessels. When disassembled in 1986, eight additional vessels at OCWD were found to have failed in the same manner but were retained by the metal cage.

The failures at Orange County in combination with the rumors of additional failures throughout the world created a crisis in confidence in the safety of the new FWFRP membrane housings. End users, suppliers and membrane companies all wondered if their FRP housings would fail during normal operation. It had become clear that the fears of FWFRP pipe suppliers were appropriate and that the manufacture of full-bore FRP membrane housings presented unique and difficult challenges in design fabrication and testing to ensure safe operation. To regain the trust of the membrane industry, the providers and suppliers of FRP products needed to take swift and appropriate action.

III. THE ASME CODE

Prior to the failures at OCWD, it was generally thought that a well-established test method used in FWFRP pipe design was adequate for design of membrane housings. American Society for Testing and Materials (ASTM) Standard D-2992, "Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings" was backed by years of pipe test data. This Standard determined allowable stress for design by subjecting FRP pipe specimens to hundreds of thousands of pressure cycles and measuring the first sign of leakage from the pipe wall. Although D-2992 was useful for design of the body wall, it was inadequate in dealing with the full bore end closure. In view of the catastrophic end failures it became evident that D-2992 did not address the issues necessary to prevent such failures.

In search of an appropriate design standard, a relatively new section of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code came to light. The ASME Boiler and Pressure Vessel Code, Section X: Fiber-Reinforced Plastic Pressure Vessels, first introduced in 1974, was created as an American National Standard to establish rules of safety regarding the design, fabrication and inspection during fabrication of FRP pressure vessels. In addition, Section X was written to create specific rules and requirements for each fabrication method, including filament winding. It became clear to some in the industry that Section X dealt appropriately with the "end closure problem" and furthermore that membrane housings were, by the laws of most states of the United States, pressure vessels subject to State Safety laws including with the requirements of Section X of the ASME Code.

In 1977, prior to the failures at OCWD, Advanced Structures, Inc. (ASI: the authors acknowledge having been employed by ASI) started making FWFRP pressure vessels specifically for membrane applications. ASI, which was the first company to specialize in membrane pressure vessel technology, felt the need to follow the ASME and to apply it to all its designs. This was not only to be as sure as possible of the safety and longevity of it's housings but also to ensure that if a failure occurred in its housings the company would not be found negligent in a court of law.

ASI also decided to adapt the philosophy of ASTM D-2992 for the body wall design margin (four times the rated pressure without weeping) in addition to the hydrostatic testing requirement of Section X (six times the rated pressure without catastrophic failure). By incorporating both into their designs, ASI was the first supplier to fabricate vessels designed to Section X standards that were also "weep fail safe". This meant that a vessel would weep water through the wall instead of failing catastrophically. Although ASI was not initially an ASME-authorized supplier, it embraced the code and promoted Section X as the standard for safe pressure vessel construction.

3.1 How Did Section X Improve Quality and Safety?

Section X is an American National Standard, legally-mandated throughout the United States and Canada and accepted by 113 counties worldwide. Unique to Section X among other pressure vessel codes and standards is it recognizes the challenges of the fabrication process. The filament winding process contains so many process variables that product consistency must be carefully controlled. In fact, Section X identifies 17 fabrication process variables that are singled out as critical to the safe operation of the vessel.

The function of Section X can be described in three sequential steps of compliance:

1. Manufacturer Accreditation: The fabricator must first prove to the National Board of Pressure Vessel Inspectors and also to an ASME-Authorized Inspector (AI) that it has the ability, integrity and total quality control system necessary to fabricate vessels that meet the standards of the ASME Code.

2. Design Qualification: The design, manufacturing procedures and materials of construction must be proven capable of producing pressure vessels that meet the requirements of the ASME Code. It is important to note that each vessel design for every operating pressure is required to go through this step in order to receive a code stamp. In this step, an ASME (AI) witnesses the fabrication and qualification test of the production prototype for each design. The fabricator produces a vessel that conforms to a specific design and that is made using a specific Procedure Specification. This vessel prototype is then cycled 100,000 times from atmospheric pressure to its design pressure. Then the cycle-tested vessel must withstand a hydrostatic qualification test and not fail at less than six times the design pressure.

3. Quality Validation: The Quality and Safety of each production vessel must be proven through production inspections and tests. Production vessels must be fabricated to the same design and procedures used on the qualified prototype. In order for a vessel to be Code-Stamped, it must be individually inspected by the AI during fabrication and testing. Included in these tests is a hydrostatic leakage test of each vessel witnessed by the AI.

For a time, the membrane industry misunderstood the intent of certain rules and somehow assumed that cycle and burst test requirements of Section X were the most relevant portion of the code. However the 100,000 cycle / six-times burst test is only ***one*** element of code compliance. The real essence of Section X was the **discipline** that required a fabricator to create designs and procedures with strict adherence to tolerances and key test criteria to ensure consistency throughout the production process. This discipline was then monitored by a third-party inspection agency to ensure that the Code was followed throughout production of a qualified design. With filament winding, process control validated by a legally-qualified independent third party is how a sound design is re-created each and every time.

3.2 The Use of the ASME Code Starts to Take Hold

As the membrane desalination industry expanded in the early 1980's there were 6 suppliers of FRP membrane housings. During this time that these suppliers started adopting ASME for its design qualification guidelines to ensure that basic vessel designs were sound. As demand for vessels continued to grow, suppliers started conforming to more sections of the code until finally in 1984, ASI became the first supplier to hold an RP (Reinforced Plastic) Code Stamp allowing them to fabricate vessels that met the entire ASME Section X Code criteria.

At first, some in the desalination industry considered the use of Section X as a marketing tool to help sell products. However, many consulting engineers were already familiar with Section VIII of the ASME Code. This Section was written specifically for the design and construction of metallic vessels. This familiarity with the ASME made them open to the use of the Section X for FRP vessels. However there were some educational challenges concerning the differences between metallic and composite vessels. Over time, as consulting engineers, other fabricators and end users were educated about the qualification and fabrication monitoring required by Section X it became clear that Section X would help provide manufacturing consistency necessary to address the problems found in the desalination industry. Finally, these products once referred to simply as pressure tubes or membrane housings became known as membrane pressure vessels.

FRP pressure vessel production rates in the early 1980s were very low. Fabrication facilities were set-up with only one winding machine because the capital required to make FRP vessels is quite high. The majority of the cost came from the highly specialized filament winding machines that were mainly sold to defense contractors and early developers of wind turbine blades. Most shops had only enough mandrels to meet one day's production requirements. Initially it was not uncommon to wind only one vessel per shift to hold six spiral membranes for 600 and 1000 PSI operation, and all vessels were endported. In these days, the winding machine was prepared, the vessel wound and then the equipment cleaned for the next shift. It is difficult to imagine now that in 1983, 24-hour production yielded only three vessels per day. At that rate it would have taken 2 ½ years for a single manufacturer to produce vessels for the desalination plant in Perth, Australia!

3.3 The Use of the Section X in Full Swing

By the 1990s, there were several suppliers making Code-stamped pressure vessels and all suppliers were embracing the rules and discipline of Section X, regardless of whether customers ordered Code vessels or not. Fabricators realized that following the process control requirements improve first-time quality, helped spot possible problems and limited their liability. So instead of being a burden, Section X compliance helped fabricators control their processes. Not only were vessels made following Code rules, each supplier had qualified all their most common products so they could be produced without waiting to qualify a design. Design qualification was done at quite an expense but deemed worthwhile to ensure safe and reliable vessels. Even if entire installations were not ordered as ASME-Stamped orders, a percentage of code vessels were specified.

During the early 1990s the industry made a major breakthrough with the development of side-ported pressure vessels. The first were HydraCode pressure vessels developed jointly by Hydranautics and ASI. The side port was the result of exhaustive testing and was limited to 1½-inch pipe size. Side porting was a significant challenge to the pressure vessel industry as it introducing even more complexity to an already difficult fabrication process.

By 1995, vessel production grew to meet market demand with many fabricators making an average of 40 to 60 vessels per day. Filament winding machines featuring two spindles were designed to double capacity without increasing labor. Many suppliers also started producing vessels on multiple production lines to push volumes even higher. However, even at these higher production volumes, the ASME Code was still used as the minimum standard for fabrication.

IV. SIGNIFICANT CHANGES IN THE FRP PRESSURE VESSEL MARKET

Within the past 10 years the industry has seen some significant changes. In 2001, Progressive Composites (one of the authors acknowledges having been employed by Progressive Composites) entered the market as a new United States supplier. They introduced many features that helped advance the technology, including large multiple-located side ports, allowing a vast reduction in manifold connections and associated costs. They also introduced the first head-interlock design that could be removed without tools while maintaining all the redundancy required for ASME conformance. Many of these new advancements were made possible by specialized programming of their four-axis winding machinery which provided superior strength to the more traditional helical winding technology. While these advances helped the company gain credibility they also raised the bar for other fabricators to create similar technology.

4.1 Market Demand Starts to take its Toll

Today, most suppliers have a minimum of two machines and as many as eight winding spindles (one spindle is required for each mandrel). Most winding machines make two shells at a time and are fabricated with only one or two employees. Most suppliers make from 40 to 90 a day on average, pushing the envelope of their process control and the ability of their employees. Most suppliers can achieve consistent quality at reasonable production levels; however, when pushed to maximum capacity, the discipline of even the most experienced fabricators is challenged. Unfortunately, almost every supplier in the industry has suffered recently with some setbacks, from side-port corrosion to erratic leaks and component failures.

During the past several years, the size of membrane systems—both brackish and sea water—grew tremendously. While systems with 500 to 750 vessels were considered very large in the 1990s, the mega-projects of today require 1300 to 2000 vessels per system. In addition, the delivery time for these systems did not significantly increase along with their size, requiring vessel suppliers to dedicate more of their capacity to mega-projects to keep their customers satisfied.

This expanding demand brought a significant change to the way vessel suppliers have operated as many suppliers started running at or near maximum capacity to complete their large projects. Although some vessel suppliers added capacity to meet this demand, most chose not to expand to keep their organizations as profitable as possible. This resulted in lead-times that were approaching 16-20 weeks for some more popular brands, forcing many original equipment manufacturers (OEMs) to search for fabricators with shorter lead-times to meet their delivery needs.

This needed capacity was met by new fabricators which, in turn, fostered commodity pricing. The newer suppliers had a lower cost structure that drove lower price points as the industry took advantage of the situation. Unfortunately, many OEMs viewed these new and inexperienced fabricators as equal to the traditional suppliers. This, in turn, forced the more experienced suppliers to reduce their pricing and redesign their products to minimize costs in order to compete.

However, the less experienced fabricators lacked the technological knowledge created from years of testing that truly challenged the capabilities of FRP materials. This forced new suppliers to attempt to copy existing technology, resulting in inferior winding technology, poor designs and inconsistent process control.

4.2 An Overconfident Market makes Fundamental Errors

Adherence to specifications and regulations for pressure vessels has relaxed over time. In an attempt to drive the cost of systems even lower, the industry has apparently forgotten many of the difficult lessons of the past and has dropped its guard as it relates to the significant risk and liability concerning pressure vessels. The ASME Code once followed by suppliers and demanded by the industry is no longer viewed as the true international or even minimum standard.

In May 2002, the regulatory community created additional confusion concerning FWFRP vessels with the introduction of the European Pressure Equipment Directive (PED). The PED was created eliminate the technical barriers of trade and to promote commerce between European Union. The goal of the PED was to harmonize the national laws of Member States regarding the design, manufacture, testing and conformity assessment of pressure equipment.

However what is not understood by many in the desalination industry is that this “new approach” calls for a flexible regulatory environment that ***<u>does not impose any detailed technical solutions</u>***. This has permitted FRP pressure vessel suppliers to once again perform their own risk analysis and to select their own design and fabrication standard, just as it was done nearly 30 years ago! The burden to determine whether a fabrication standard is adequate has now been placed on the regulating jurisdiction with little understanding of the risk and liability involved.

Although ASME Section X is accepted by the PED (with slight modification), not all European suppliers have continued to use it. Some have reduced the required design margin by over 30%. What is also of concern is the PED hydro-test pressure requirement of 1.43 times design pressure compared to the Section X requirement of 1.1 times the design pressure. The lower hydro-test pressure requirement under Section X was adapted in recent years to prevent damage to the vessel during hydro-testing.

V. FRP PRESSURE VESSELS TODAY

While most FRP pressure vessel suppliers have an ASME Certificate of Authorization, it is rarely used to stamp vessels and many new fabricators do not even qualify their designs to Section X. These days, third-party certification and actual code-stamped vessels are a thing of the past. Although ASME terminology may be included in required documentation, a one-day audit now replaces independent third-party inspection throughout fabrication. Today there is no emphasis on the same standard that has kept the industry safe for the past 25 plus years, making the requirement useless and hollow.

In today's market, pressure vessels are treated as a commodity and suppliers are making more vessels per hour than ever before, although the technology used to make these vessels is more complex than ever before. Experienced suppliers are now trying to reduce cost to remain profitable while trying to make the most complicated products they have ever made. In addition, when new OEMs, end users and inexperienced fabricators are factored into the equation, the separations industry is taking significant risk, perhaps without even realizing it.

Is the desalination industry doomed to repeat the mistakes of the past? With the volume of vessels required for each project and the delivery demands for these projects, the likelihood of mistakes is very high. This industry must recognize that any failures that may happen today or in the future will come with significant risk and liability. Every fabricator, OEM, engineering company and end user must understand the entire desalination industry will suffer if there is just one vessel failure resulting in a death or damage to a system.

5.1 Section X Continues to Evolve

Some OEMs and end users that have been in the industry for years may remember the ASME Code as a difficult standard that added time to project procurement and additional cost to every vessel. However, it should be noted that with today's volume of production the cost per vessel to get an actual code stamp is significantly less than it was years ago.

Based on the volume of a desalination project, the total cost of an ASME Code Stamp per vessel now ranges from 1½ to 4 percent of the vessel price. This price is not just for a vessel that is made to the code; it is for a vessel that carries full ASME certification by an independent third party inspection agency specializing in vessel inspection. So the cost of certification should no longer be the problem that it was years ago.

In fact, as a result of petitions to the ASME by active users of Section X, the Code evolves over time to embrace new techniques and logical reasoning. This has made the ASME Code more cost effective and fabrication-friendly for large projects while still embracing the original intention of assuring safety and quality. Some of the latest developments are as follows:

1) Vessels that are identical in every detail except length can now be qualified as a series. This greatly reduces the cost of qualification for the supplier and also reduces the time to qualify a product line.

2) ASME permits the fabricator to reduce the amount of qualification testing by allowing them to qualify each design with the largest nozzles (side ports) and the most port locations. Designs with smaller ports and fewer port locations do not required additional qualification testing.

3) ASME now has alternate inspection rules designed specifically for large projects that help reduce the cost of third-party inspection for 24-hour operations.

VI. DETECTING IMPERFECTIONS

So what can be done if you are responsible for several hundred or several thousand vessels that were ordered without a Code stamp? End users and OEMs must understand that there is no way to stamp vessels after they have been fabricated. In addition, there is no way for anyone to guarantee the safety and service life of vessels already produced that were not fabricated, inspected and stamped per ASME Section X requirements.

Having said that, what can and should be done to help limit the problems that might arise with vessels that were not fabricated in accordance with ASME rules and regulations? The true problem is that many important variable details are buried deep into each individual unit. Many related problems cannot be detected externally or inspected without damaging the vessel. However, with a little experience (or in this case guidance), some vessel inconsistencies may be detected visually to help minimize the potential of premature vessel failure.

Outside Body Wall Surface – Wavy: This condition happens when the band advance in winding was rendered incorrect, either by a machine error or by removal of a defect through unwinding and rewinding. A wavy surface can also be caused by an incorrect bandwidth, either too narrow or too wide. These vessels will not have adequate strength and may leak prematurely in service.

Outside Surface – Dry: This dryness is detected when you can actually see the roving pattern on the outside surface. This vessel did not properly rotate during the curing cycle and resin dripped away during exotherm creating a dry surface or sometimes an axial streak. This will shorten vessel life.

Outside Surface Body Diameter Inconsistent: A vessel that is thicker on the body wall at one end and then tapers to be thinner as each measurement is taken had a strand tension problem. In this case, the fiber content in the thin end will be higher and most likely significantly stronger. In the thicker portion of the vessel, the resin content is higher and more likely to fail in service, possibly catastrophically.

Body Diameter Undersize More Than 2.5mm (.100 inch): It is recommended that all vessels are measured at the body wall. Any vessel that is significantly undersize (more than 2.5mm) may be missing a helical layer. Each layer of material placed during winding adds strength. It is not uncommon for machines to error and drop a helical layer. In some designs, such drops can make a vessel very unsafe to use and can result in catastrophic failure. In addition, the axial growth under pressure of a too-thin vessel will also result in excessive secondary damage from over-stress.

Bell Diameter - Over or Under Specification: The bell at each end of the vessel is very important when it come to safety because this is where past failures have occurred. Bells that are significantly over or under sized can indicate too much resin or missing material, either of which will make the vessel weak. Typically these problems are caused by excessively high or low strand tension that tends to affect vessel bells more than body walls. Bell consistency is extremely important.

Bell Profile – Different at Each End: When the bell profile at each end of the vessel is different, this indicates a problem with placement of the material, sometimes called program "offset". In this case, one bell will be very strong and one will be very weak. This is a very dangerous condition.

Cracking in the Laminate near the Side Ports: By cracking near the side ports, we are not speaking about cracks where the metal and the fiberglass meet as this is typical during the expansion of the vessel. Instead we are targeting cracks in the fiberglass surface radiating away from the side port. This is a sign of significant weakness. This is usually caused by insufficient material to support the side port or from a machining operation that is not to specification or a vessel bell that is under-sized.

Radial Cracking in the Bell Transition Area: Problems can occur where the bell diameter meets the body diameter of an FRP vessel, especially in seawater designs where the two diameters are very different. A radial crack in this transition is an indication of improper band width closure. This is a dangerous condition.

Rough Inside Surface: A rough inside surface of the vessel is usually caused by a curing problem and typically means the vessel was either under cured or had the wrong ratio of resin to hardener. This will be most significant in the vessel bell area and not as much in the vessel body.

Color Variation from Vessel to Vessel: Vessel resin color should be very consistent from vessel to vessel. When this is not the case, the problem is usually related to vessel cure. Lighter colors mean under-cured material while very dark brown indicates over-cured material. Some say that there is no such thing as an over-cured epoxy, however, such vessels will be very brittle.

White Areas Outboard of the Locking Ring: Any white areas outboard of the head retaining groove indicate a delamination either from excessive pressure or hydrostatic test time or poor fabrication practices. This is the initial damage that can lead to vessel failure. Vessels with this damage should be immediately removed from service as they are in early stages of catastrophic failure.

If You Find Something, What Should You Do? If any problem is found during an inspection, the fabricator should be notified for replacement, extended warranty and/or close monitoring of the situation. All prudent precautions should be taken to avoid damage to life and property. The fabricator has the ultimate responsibility to prevent catastrophic failure.

The industry must remember that if there is a vessel failure on a system of any size, all the remaining vessels should be replaced without question unless there is <u>overwhelming evidence</u> that the problem can be isolated to the satisfaction of all involved and that the system can continue to operate safely without question.

VII. CONCLUSIONS

To overcome problems with corrosion and also with the dimensional shortcomings of steel pipe, thirty years ago the membrane separations industry began to standardize on FWFRP membrane housings. Almost immediately, catastrophic pressure vessel failures exposed serious design flaws and shortcomings production-process control. Over the course of ten years, Section X of the ASME Code emerged to provide the structure upon which confidence in FWFRP housings was based. Implementation of the code helped eliminate poorly made housings and provided legal protection from charges of negligence. For the last twenty years, strict adherence to the ASME Code and third-party inspectors have helped keep the industry safe.

Within the past few years, the industry appears to have forgotten the problems of the past and has relaxed its reliance on Section X, just at a time when vessel production and new fabricators entering the market are at an al- time high. The combination of these factors presents a real possibility of catastrophic failure of FWFRP pressure vessels occurring once again.

Although there are many visual defects that end users can check and hopefully identify the most egregious of errors, the only real solution for the industry is to once again embrace the evolving rules of ASME Section X for FWFRP pressure vessels, including independent third-party inspection and certification.