Non-Destructive Condition Assessment of Fiberglass Reinforced Structures

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ABSTRACT

Fiberglass reinforced plastic (FRP) is used in wastewater processing for tanks, scrubbers, piping, ducting and other equipment. FRP often provides better corrosion resistance at lower cost than stainless steel. For some applications, regulators require structural evaluation of containers or piping for public health and safety purposes. In addition, most asset management programs require periodic inspection and evaluation of the remaining service life. Traditional inspection of FRP does not provide results that calculate the remaining service life of the asset. In the case of piping and ducting, traditional methods are very limited and often no inspection occurs. UTComp has developed and proven a non-intrusive and non-destructive test method that provides objective data that is used to evaluate the current condition of FRP, including piping and ducting up to the largest storage tanks and provides prediction of the remaining service life. An overview of this technology is presented followed by case studies.

KEYWORDS: Fiberglass reinforced plastic, FRP, non-destructive testing, predictive maintenance, remaining service life, suitability for service, fitness for service

INTRODUCTION

FRP is widely used for tanks, scrubbers, piping and ducting and other equipment in wastewater treatment for corrosion resistance, particularly for solutions that are acidic or have free chlorides, at moderate temperatures. Common applications include containment of solutions including brine, chlorine dioxide, chlorine, sodium hypochlorite, sodium bisulphite and numerous acids. All of these applications rely on the corrosion resistance and structural capacity of FRP. For many applications, the cost of FRP equipment is lower than for stainless steel (Lieser, 2013).

The central case in this paper covers structural evaluation of an atmospheric storage tank used for ferric chloride at the wastewater treatment facility for the City of Ottawa in Canada. Ottawa is the capital city of Canada, with a population of about 1,000,000 people.

The Robert O. Pickard Environmental Center (Pickard) in Ottawa, Canada is a 545,000 cubic meter per day secondary treatment facility. In 2013, the facility had identified the need for structural assessment of fiberglass reinforced plastic (FRP) tanks used for chemical storage. This particular situation was to determine if the FRP roofs were able to support personnel loads during maintenance work. The scope of the work was expanded to include evaluation of the tanks to assess their suitability for service, and to allow planning for asset maintenance, repair and replacement needs. This paper describes the evaluation of one of these tanks.

This introduction gives some background for evaluation of FRP.

Fundamentals of FRP Construction

It is generally understood that FRP is composed of 2 primary materials - resin and glass comprise more than 98% of most FRP. Each material plays an important role in the properties of the FRP. The roles of these constituent materials are outlined in Table 1.

Table 1 – FRP Constituent Materials

Constituent	Details
Resin	- Most commonly discussed component of FRP - Functions as the "glue" that binds the structure and makes it leak-tight - Provides a significant portion of the corrosion and chemical resistance properties of FRP - Comprises 40% to 80% of a corrosion FRP structure - Provides 12% to 45% of the strength of the FRP - It is common to identify the FRP by the specific resin used
Glass Fiber Reinforcement	- Not commonly discussed in detail in the design stage - Primary purpose is to provide structural strength in the direction of the glass fiber. - Allows FRP strength to be tailored for the loads by controlling fiber orientation - Comprises 20% to 60% of a corrosion FRP structure - Provides 55% to 88% of the strength of the FRP

Occasionally, reinforcement of specific, non-structural corrosion resistant layers might have a polyester reinforcement added, rather than glass.

Typical FRP construction for corrosion applications is illustrated in Figure 1. The photo shows how FRP is normally constructed for a corrosion application. The glass/resin fractions can be changed through the thickness and the glass fiber orientation can be modified to provide specific structural properties.

In this Figure, the portion of the cross-section at the mold side (top), labelled "Corrosion Barrier", is constructed to give more corrosion resistance by using a high fraction of resin and short strands of randomly oriented glass fibers. The innermost layer of this section, 0.25mm thick, is 90% resin and 10% reinforcement, using a thin reinforcement fabric. The section marked "Structural Layers" has higher glass fraction and examination of the photo will show that the glass fibers are oriented. The outer layers at the bottom of the photo are made in a similar manner to the Corrosion Barrier and are placed for protection from the external environment.

For design of FRP for corrosion applications, it can be specified that strength contributions from the corrosion barrier be removed from the calculations, so that only the structural portion is considered to support stresses from operating loads. This approach is almost identical to the use of "Corrosion Allowance" in ASME boiler and pipe calculations. When constructed, the

corrosion barrier does contribute to the strength of the FRP. When FRP has been well constructed, separation between the corrosion barrier and the structural layers cannot be detected.

As a further comparison, safety factors of 6 to 10 are normally used to determine FRP allowable stresses, where a safety factor of 1.6 is used for many steel products.
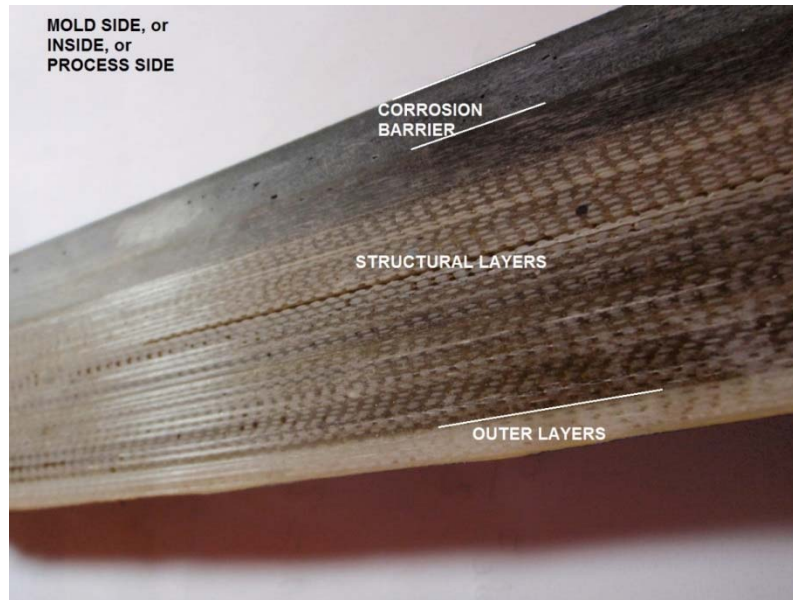

Figure 1. Cross-section of FRP showing typical construction for corrosive fluid containment.

Inspection and Evaluation of FRP

The purpose of inspection and evaluation of FRP is to determine the current condition of the asset and to identify short and long term repairs that may be required. Reliable performance of FRP in structural applications requires non-destructive methods that can verify structural properties including mechanical strength, or the structural capacity of the FRP. Using non-destructive methods, regular evaluations can be completed to monitor changes in FRP condition. The results of reliable non-destructive methods can be used to predict remaining service life of FRP equipment.

Traditional inspection methods for FRP are centered on visual inspection of the inner surface of the FRP which requires emptying the asset and "intrusive" inspection with confined space entry or cutting a piece out of the asset for localized inspection (with the additional costs and risks forced by repair). When confined space entry is made, the inspection will also include a team of personnel for support as well as increased risk to the facility as a whole. The results of these intrusive inspections should normally include a set of observations and measurements made by the inspector. They may also include thickness of the corrosion barrier from chipping or drilling a countersink into the corrosion barrier, thus damaging the existing corrosion protection. The report may not include any quantitative evaluation of the current structural capacity of the FRP, or prediction of the remaining service life.

There are few standards that describe methodology or criteria for FRP inspections once assets are placed in service. There are no peer-reviewed standards published by any North American standards organization such as ASTM International (ASTM), American Society of Mechanical Engineers, (ASME), American Water Works Association (AWWA), American Society of Civil Engineers (ASCE), or American Petroleum Institute (API).

Some users of FRP have established procedures for assessing structural integrity of FRP using Acoustic Emission (AE) testing. AE testing is completed on equipment that is removed from service and emptied. Sound sensors are applied to the surface of the FRP and the equipment is loaded up to a specified test load in pre-determined steps. Sound pulses generated by FRP under load at each step are counted and the analyst determines whether the FRP in its current state is able to carry its design loads. AE testing has the following key characteristics:
- If the test load creates sound pulses, then it assumed that the FRP is irreversibly damaged, and
- Any change in strength or capacity of the FRP is not quantified, either from one test to the next or for any test on a stand-alone basis, and
- No prediction of remaining service life or suitability for service can be provided, and
- No quantitative information is provided to assist with engineering any amendments or upgrades to the equipment, and
- No information is provided regarding the condition of the corrosion barrier, and
- The only result that can come from the test is whether it passes the criteria at the time of the test.

Another conventional method used to determine the structural capacity of FRP is to perform destructive tests using standard test methods.

Destructive testing has the following key characteristics:
- A single sample removed will only provide information on a small area of the FRP, and
- Removal of samples creates immediate need for engineered structural repairs, and
- The destructive test results provide quantification of the local change in strength of the FRP while in service, and
- No information is available from openings, attachments or penetrations and their reinforcements, and
- Information is available to assist with engineering amendments or upgrades, and
- Some prediction of remaining service life can be provided.

The inspection and evaluation methods described above are all intrusive and in the case of destructive testing also cause damage to the FRP.

The facility engineer at Pickard requested an advanced method that he had used while working in an industrial facility. The third method is known as the UTComp® System which uses a novel application of ultrasonic equipment to take readings from the surface of FRP to be evaluated. The readings are then analyzed to determine the current structural properties of the FRP, both locally and for major sections of the structure. This innovative method has the following key characteristics:

- In most cases the testing is non-intrusive, not requiring any confined space entry, and
- In most cases the testing can be done while the FRP equipment is in use, and
- The method is non-destructive and evaluates condition without imposing any changes to the FRP, and
- Reinforcements at openings, penetrations, and attachments can be included, and
- The basic technology had been developed by NASA, and
- Engineering analysis can be done using the results, and
- Prediction of remaining service life can be made from the results.

This inspection process has been used to inspect more than 1,500 FRP vessels and tanks in industrial and chemical processing facilities since 2008. In that time several potential failures have been detected and prevented. There have been no unexpected failures of any FRP that is being monitored in this way.

Property Changes in FRP

Many users of structural FRP can report where the structural capacity of the FRP has reduced while it has been in service. There have been numerous investigations into this phenomenon[6,7,8], including proposed models of the causes of these changes. It is beyond the scope of this paper to identify or categorize these changes or models.

Figure 2 shows the results from tests of samples removed from a glass reinforced tank on two (2) occasions. The tank had been in service storing a corrosive liquid. The results shown are for the measured thickness of the tank shell and the results of destructive testing. The results of the tests are shown as percentages as given by equation (1) below. Clearly the new values should be 100%

$$Percentage\ of\ Original = \frac{Current\ Measurement}{Original\ Measurement}\ x\ 100\% \tag{1}$$
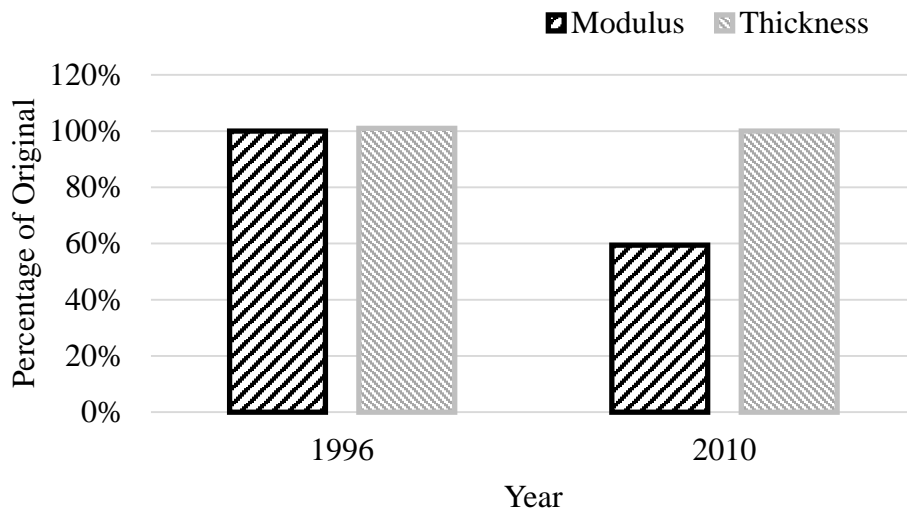
Figure 2. Destructive Test Results from Samples Removed from Glass Fiber Reinforced Tank Shell

From Figure 2, it can be seen that during fourteen (14) years of service, the thickness of the laminate did not change appreciably but the modulus reduced by 40%. At some point in this decline, it is likely that the composite will no longer be able to support the required loads. The corrosion barrier as shown in Figure 1 also experiences changes from service conditions. Some of these are illustrated in Figure 3. In addition, blisters can form and the resin can be softened by chemical attack and corrosion.
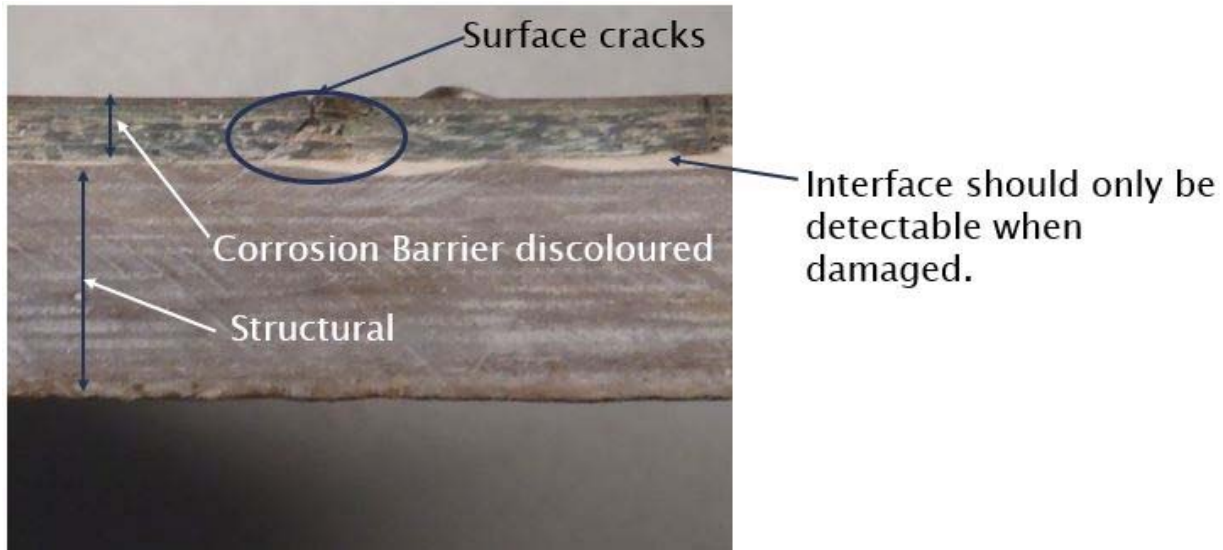

Figure 3. Illustration of effects on the corrosion barrier from service conditions. Note the different appearance of corrosion barrier and structural.

The UTComp System uses ultrasound to determine changes that have occurred to FRP.

Basic Ultrasonic Testing Principles

The first patent application regarding use of ultrasound for testing materials was made in 1940 by Dr. Floyd Firestone at the University of Michigan. This first patent, and most subsequent work using ultrasound identified that invisible inhomogeneities within materials could be detected. For most of the 75 years since the first patent application, the focus of ultrasonic testing has been on metals. In the case of ultrasound, a pressure pulse is applied to material and inhomogeneities are detected when a feature blocks some of the path – features that are parallel to the path direction are generally not detected.

Use of fiber reinforced polymer composites for structural applications has been pursued since the 1930's, and has seen significant changes in the matrices and fibers available. With the growth of commercial aircraft starting in the 1960's, many investigations were conducted into use of ultrasound to detect flaws and defects in composites. Because many fiber reinforced composites are made in layers, interfaces between layers often interrupt the path of the pressure pulses and show as features or possible defects for most ultrasonic techniques. Ultrasound is the most common non-destructive technology used for composite materials.

Ultrasonic pulses can be applied to materials in three main modes:
- pulse-echo, where the pulse is applied to the surface by the same transducer that receives reflected energy from within the material,
- thru-transmission, where the pulse is applied to one surface by one transducer and the pulses that pass through the material are received by a transducer placed on the opposite surface, and
- pitch-catch, where the pulse is applied to the surface by one transducer and another transducer on the same surface receives reflected energy within the material.

In ultrasonic testing, an energy pulse is applied to the face of a material by an actuator, or transducer. These pulses have a short wavelength which translates into a wave frequency in the range listed above.

Currently, the most common use of ultrasound in FRP is in thickness measurement of new FRP structures. Thickness measurements are usually made by following this process:
1. A reference standard is used which duplicates the material to be measured with a known thickness so that the transit time of the reflected signal can be used to determine the sonic velocity through the reference standard
2. It is assumed that the sonic velocity through the material to be measured is the same as the reference standard.
3. The transit time of ultrasonic pulses applied to the material is converted into thickness.
Thickness testing does not use any other information contained in the returned ultrasound signal.

As for metal structures, flaws such as voids, porosity and planar defects that interrupt the path of the ultrasonic wave through a fiber reinforced composite may appear on the display of the instrument and can sometimes be identified by a skilled analyst. This principle is used for evaluating composites in some applications, aerospace in particular. In some cases, defects in FRP do not appear explicitly.

Propagation of sound waves through a medium is affected by changes along the wave path. Examples of these changes could be foreign objects, gaps or bubbles, changes in the crystal structure of the material, and others. In the case of fiber reinforced composite materials, the structure of the material always includes some (and sometimes all) of these changes along any wave path. These generally show as attenuation of any signal that passes through the material as well as visible indications on the test instrument. For glass reinforced composites, normal variations that occur because of materials and processes used would often be cause for rejection using the criteria that have been adopted for metals.

Summary of Earlier Investigations into Ultrasound with Fiber Reinforced Composites

In the early 1960's, use of ultrasonic testing (UT) was already showing reliable results for finding flaws in metallic structures. One of the desirable attributes of this technique is that reliable data could be generated if only one side of the material under investigation was accessible. This meant that in addition to finding flaws or defects, the same techniques could be used to produce thickness records of reasonable accuracy. At the same time, use of composite materials such as glass reinforced thermoset plastics was being explored for a number of

structural and corrosion-resistant applications. Starting in the mid 1960's, researchers started to examine uses of ultrasound with these fiber-reinforced composite materials.

A series of investigations (Vary & Lark, 1979) applied ultrasonic pulses to composites and received the responses using acousto-ultrasonic devices, thus mixing the principles of ultrasound with acoustic emission testing. This process is known as "acousto-ultrasonic" because the forces applied to the specimen are from ultrasonic pulses, whereas for acoustic emission, the forces applied to the composite are from mechanical loads applied, such as pressures and weights. In both cases, the responses are received in real time by acoustical equipment. This work showed correlation between attenuation of the signal transmitted through the full thickness of a laminate – across its layers - and its tensile strength parallel to its layers.

It is important to note that the correlation does not mean that the value of the elastic modulus can be determined directly from the acousto-ultrasonic data. To determine the actual modulus it is necessary to know the modulus value corresponding to an acousto-ultrasonic value at one point along the curve.

Since the above work was completed, further work has developed procedures and methods that use standard ultrasonic equipment and transducers. These novel methods have actually simplified the field requirements for inspection, including calibration (Clarkson, 2014). Calculations are performed on the ultrasonic results to produce a number of parameters that are used to determine the Percentage of Original as given in equation 1.

Determining the Condition of FRP in Corrosion Service

Reliable performance of FRP in structural and corrosion applications, especially where life prediction is desired, requires non-destructive methods that can verify the current properties including mechanical strength. With availability of reliable non-destructive methods, regular evaluations can be completed to monitor condition. When these evaluations produce quantitative results, calculations can be completed to predict the remaining time when the FRP will be suitable for service (Remaining Service Life or RSL). Another term for "Suitability for Service" is "Fitness for Service".

At this writing, for industrial and civil applications, non-destructive methods are not widely used to determine whether a FRP structure is suitable for service or to calculate RSL. Furthermore, for FRP structures that have been in service for some time, relevant non-destructive data is rarely available from the new structure, which limits meaningful comparisons related to changes that have occurred and thus the current suitability for service.

First, consider a parallel situation where a steel structure is to be evaluated. For steel, structural capacity is generally related directly to thickness. In this case, the original thickness is documented, say on a drawing or specification. Conventional non-destructive methods can be used to reliably determine the current thickness of the steel – if material loss from corrosion or abrasion has occurred, the thickness will be reduced. It is reasonable to use the original documented thickness as the starting thickness, even if the actual thickness was different. From the starting thickness, the rate of thickness change can be determined and life prediction of the structure can be estimated, even when measurements might not be available.   If the starting

thickness assumption was not correct, collecting periodic data will allow the rate of change to be determined and RSL can be predicted. This is illustrated in Figure 4.
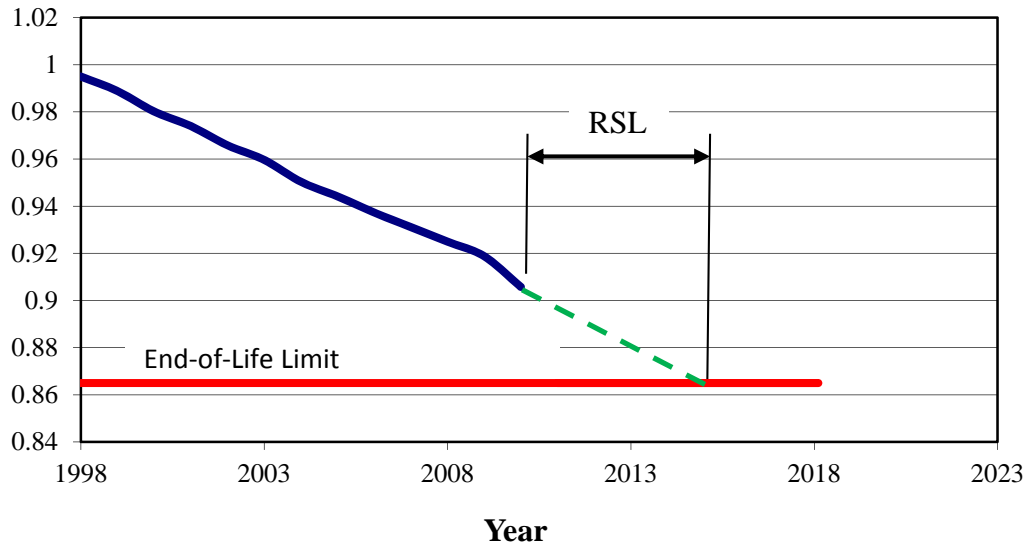

Figure 4. Illustration of how thickness measurements on a steel vessel can be used to determine Remaining Service Life.

Now consider a FRP tank where thickness is not expected to change but the modulus does and the condition of the inner corrosion barrier may also change. In this case, the ultrasonic methods (Clarkson, 2014) described above can determine the current relative modulus value. In order to create a prediction of the rate of modulus change, it will be necessary to have a starting value or a series of concurrent data points that will allow the shape of the curve to be determined.   In most cases, it is reasonable to assume that the new FRP had a modulus of 100% of the expected value and this can be used as the initial start point.

An additional dimension for FRP is the condition of the corrosion barrier as discussed above. The UTComp System analysis detects damage to the corrosion barrier without entering the tank. In fact, corrosion barrier analysis is usually most effective when the tank is in normal operation. Damage is detected by considering the shape of the reflection from the inner surface and differences in the ultrasonic reflection at the liquid level, when applicable.

CASE STUDY

The tank that was inspected for this study is in service storing ferrous chloride solution. Ferrous chloride solution is acidic and corrosive. Solution pH is normally less than 2.1. For this service, FRP is a good material choice (Ashland Chemicals, 2010).

The tank configuration is shown schematically in Figure 5. Tank inside diameter is 4.1m (13.5 ft) and overflow height is 6.1m (20 ft). The tank has a ladder to the top head attached to the shell. The top head has a non-slip coating applied. The tank was manufactured in 1990 and was 23 years old at the first inspection. The tank shell thickness changes at 3m elevation.

Figure 5. Configuration of Ferrous Chloride Tank. Ladder, overflow and some nozzles are not shown.

This work was commissioned to achieve several objectives.
- Determine the structural condition of the top head to allow personnel loads for maintenance activities, and
- Assess the bonding of the ladder attachments to the shell, and
- Evaluate the condition of the tank and determine the remaining service life.

Below are the conditions at the time of the inspection in December 2013:
- Tank located indoors.
- Ambient temperature about 10°C (50°F).
- Tank was in service. Ferrous chloride solution to depth of about 2.5m (8ft). There was no access available to the inside of the tank.

Inspection

Table 2 summarizes the inspection plan that was used. In the table, the term "repad" refers to a reinforcing pad. Repads are added to FRP sections to provide local increase of structural capacity. In the details for the ultrasonic inspections, a minimum of thirty (30) readings are specified to ensure that a meaningful distribution of the results is obtained.

Access to the top head was unavailable for this inspection and the top head has a non-slip surface which can affect readings. The owner decided to proceed with the inspections that were possible at this time and to plan top head inspection for a future inspection. To obtain readings from the

top head from the outer surface, it is normally recommended to remove the non-slip coating at measurement locations. Each reading only requires a 32mm (1.25") diameter circular area to be cleaned.

Table 2 – Inspection Plan

Inspection Type	Description		
External Inspection	Systematic visual inspection of the following items: support structure, external condition, external components, pipe and nozzle connections. Record on checklist.		
Ultrasonic Inspection	**Tank Section**	**Repad**	**Details**
	Shell at 1m Elevation	N/A	Take at least 30 readings from outer surface.
	Shell at liquid level	N/A	Take readings above and below liquid level.
	Shell at 3m Elevation	N/A	Take at least 30 readings from outer surface. The shell thickness at this elevation to the top is less than at 1m.
	Tank Top Head	N/A	Site conditions did not allow access at this inspection.
	Shell at 1m Elevation	Manway	Take at least 30 readings equally spaced around repad midway between outer and inner radius.
	Shell	Ladder Attachments	Several readings from each attachment.

All available inspections could be completed from outside the vessel in its current status. In some cases, Personal Protective Equipment (PPE) for fall protection was required. All inspection activities were completed by one inspector. In general, the inspection time for one asset by a trained inspector can range from one (1) to several hours, depending upon scope, vessel size and site requirements.

External inspection was completed by following a written procedure that is based on API 653 (American Petroleum Institute, 2009). Figure 6 shows some examples of items inspected. In almost all cases, analysis of these visual inspection results can be done by following a logical process similar to a computer program flowchart. In fact, for the external inspection for this tank, the analysis was completed by a computer program and the results were verified by an engineer with extensive experience in the FRP field.

a) Hold-down Lugs

b) Nozzles and Flanges

c) Ladder Attachments

d) Pipes and Supports

Figure 6. Examples of items inspected visually as part of the tank inspection.

The ultrasonic inspection was also conducted by taking readings at the locations stipulated in Table 2. Figure 7 shows a typical view of an inspector taking readings.

Figure 7. Typical view of a trained inspector taking ultrasonic readings on FRP tank.

Inspection Results

Analysis of the external inspection revealed two defects.

Overflow leaks had occurred from the manway on the tank roof. Filling the tank to this level can pressurize the tank and cause damage at the hold-down lugs and tank floor. The best prevention of this problem is to place an overflow at the top of the tank cylinder which will direct excess fluid to a safe location. An alternative is to control the level with instrumentation, but this may not fully prevent overfilling.

The tank did not have a vent to allow air to move in and out of the tank with level changes. A "soft" vent at the roof manway existed, but if the manway was tightened with a gasket, this would no longer vent.

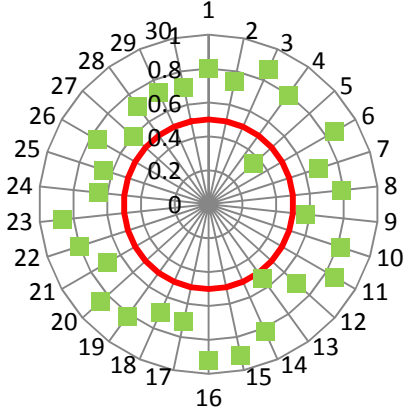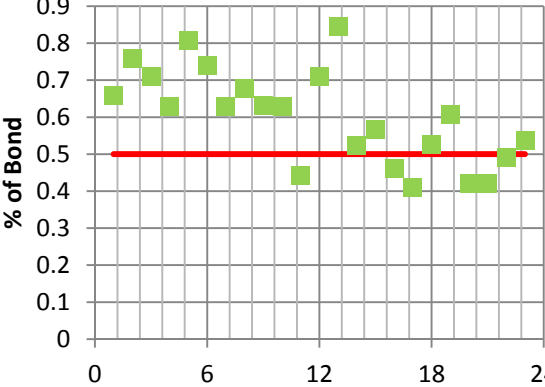Analysis of the ultrasonic readings for the shell sections is summarized in Table 3.

Table 3 – Results from Ultrasonic Readings for Sections

Section	Results
Shell at 1m Elevation	Ferrous chloride has permeated the corrosion barrier to about 0.4mm. Current Strength is 82% of the design value - small decline with no damage.
Shell at liquid level	Negligible damage to the corrosion barrier from the ferrous chloride.
Shell at 3m Elevation	No visible ferrous chloride permeation detected. Current Strength is 57% of the design value - minor decline with no damage.
Shell at 1m Elevation	3% of readings were not fully bonded – this is considered to be minor. Thickness exceeds the minimum.

The results of the ultrasonic analysis for the repads are summarized in Table 4. Bonding of reinforcements applied and vessel sections was determined as Percentage of Theoretical Bonding. Many design specifications consider the possibility that secondary bonds, such as those used to attach reinforcing pads, may have as little as 50% of their theoretical shear strength. For this reason, this analysis uses the criterion that a bond exists when the percentage shown in the results is greater than 50%. If 2 or more consecutive points or more than 25% of the points are not bonded, immediate repair is recommended. For each repad a graphical plot is provided to show the results.

In the plots, the red line shows the acceptable bonding threshold.

Table 4 - Results from Ultrasonic Readings for Repads

Repad	Results	
Manway repad	3% of readings were not fully bonded – this is considered to be minor. Thickness exceeds the minimum. Circumferential position shows reading location. Radial position shows percentage of bond.	
Ladder attachments	26% of readings were not fully bonded – this is considered to be high. Thickness exceeds the minimum. The attachments where bonding is less than the threshold are identified so that repairs can be targeted.	

Remaining Service Life Prediction

Remaining service life (RSL) can be calculated if the FRP tank has been designed and built according to a recognized standard, or after engineering analysis. This provides knowledge of the design approach used and the actual safety factors in place.

RSL is calculated as the time from the current inspection to the projected date when the FRP in the tank reaches a "Safety Factor" of 2. Using this method, the FRP equipment can be replaced or repaired proactively.

The engineer analyzing the inspection data has experience with the manufacturer of the tank and was confident that the tank was designed and built in accordance with recognized standards and used a safety factor of 10 at design. Based on this, the Safety Factor of 2 will be at 20% of the design, or new value.

Experience with FRP equipment in a wide range of applications also indicates that reliability can become uncertain when the current strength reaches 40% of the design value. When this occurs, an engineering review is recommended in which a competent engineer determines fitness for service along with any new limits that may be required.

Figure 8 presents a graphical illustration of this projection. Periodic inspections, normally at 3 year intervals, are recommended to monitor any developing changes. Note that this tank is expected to be serviceable for 20 years after the current inspection.
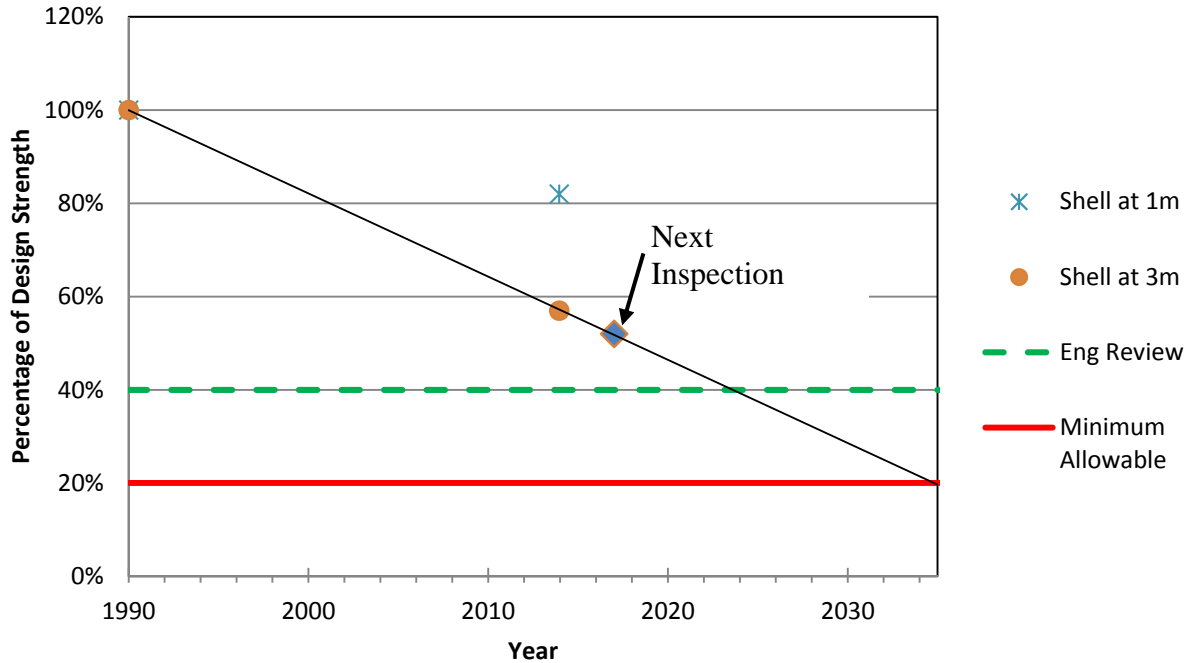

Figure 8. Graphical Remaining Service Life projection of the tank from 2013 inspection.

Conclusions
- Some repairs are required.
- Projected end of service life is 2033.
- Condition of corrosion barrier and structural FRP was determined while the tank was in service and without confined space entry.

Recommendations

The following recommendations were made from the inspection:
- Install overfill protection and venting on the tank.
- Repair the defective ladder attachments.
- Inspect the top head at next inspection.
- Inspect again in 3 years.

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