The Origin of CARP and the Term "Felicity Effect"

Timothy J. FOWLER, Spicewood, TX, USA
howzatwk@verizon.net

Abstract. The importance of the Felicity effect became apparent in the 1970s when research groups investigated the acoustic emission (AE) properties of glass fiber reinforced thermoset plastics (FRP). Interest in FRP laminates was stimulated by the poor performance of tanks, vessels, and process equipment fabricated from the material. Failures ranged from minor leaks to catastrophic rupture. The lack of a non-destructive test for evaluating their structural adequacy contributed to the problem.

Exploratory research began in 1974 with the goal of assessing the value of AE as a non-destructive test of FRP. The study concluded that, even though AE testing was in its infancy, the method showed promise. Laminates were found to emit copious amounts of emission. Investigators recommended focusing on the Felicity effect, emission during load hold, and high amplitude events. The term "Felicity effect" was adopted by the groups involved in the research. A complementary program showed that for corroded FRP the load at onset of emission is a sensitive indicator of reduced failure strength.

Twenty-seven individuals representing eleven organizations with a range of interests attended a key meeting in December 1977. The meeting resulted in the formation of the Committee on Acoustic Emission from Reinforced Plastics (CARP), which was established under the auspices of the Society of the Plastics Industry. During 1978-82 CARP coordinated a series of research, and development programs. The result of these multiple studies was the January 1982 publication of "The Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Tanks/Vessels". Today, the provisions of the CARP document are the basis of most FRP standards.

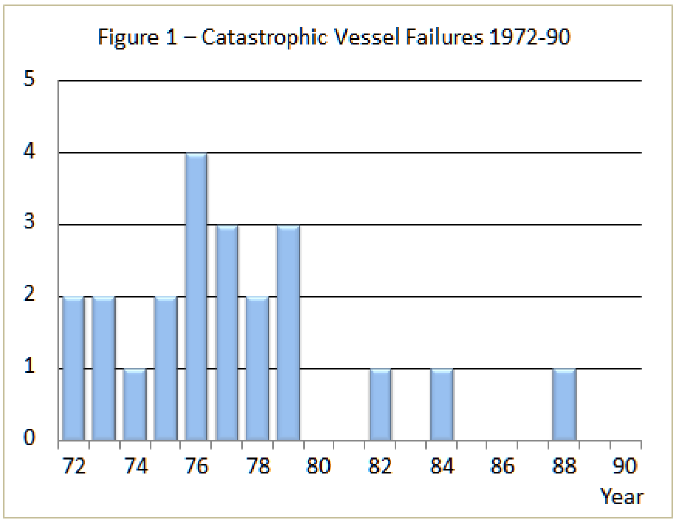
The following ASTM terminology applies:

- Felicity effect: "The presence of detectable acoustic emission at a fixed predetermined sensitivity level at stress levels below those previously applied".
- Felicity ratio: "The ratio of the stress at which the Felicity effect occurs to the previously applied maximum stress".

The term "vessel" is used to describe pressure vessels, tanks, and other process equipment. Vessels are fabricated from glass fiber-reinforced thermoset plastic (FRP). The plastic matrix is also referred to as "resin". The most commonly used plastics are vinyl ester, polyester, and epoxy. Thermoplastics do not have a similar acoustic emission (AE) signature and are not covered by the CARP procedure. The primary reinforcement is glass. Continuous filament wound fiber, strand, roving, mat and chopped fiber reinforcements are included. The many forms of mat construction include chopped strand, random fiber, woven roving, and continuous fiber.

1.0 FRP Problem

Corrosion resistance is recognized as an important property of FRP and, in the 1960s, the chemical process industry began to use the material for construction of vessels and piping. Unfortunately, early use of FRP met with limited success and a number of serious in-service failures occurred. Figure 1 shows catastrophic failures of Monsanto Company FRP vessels for the nineteen year period 1972-90. Accurate numbers are not available for the years prior to 1972, although it is known that a similar performance pattern occurred. Catastrophic failures are defined as failures that result in release of the vessel contents within four hours. Numerous minor failures were also reported including: leaks, cracks at nozzles, cracks in shell to head discontinuity areas and at stiffeners, breakage of hold down lugs and attachments, internal surface cracking, and blistering. The failure problem was an industry-wide problem and not unique to Monsanto. Interest in using AE for non-destructive testing (NDT) of FRP laminates was stimulated by the poor performance of vessels fabricated from the material and resulted in development and publication of a test procedure [1].



Personnel safety is of primary importance. Even if catastrophic failures can be avoided, the minor failures described above are not acceptable. Taking steps to protect personnel from injury and exposure is not an adequate solution. Failures create economic and environmental issues that work against the use of FRP vessels. These considerations led Monsanto to adopt a policy of not purchasing FRP vessels until their safe use could be assured. Reasons for the problems with FRP vessels are varied, but include:

- Use of metal vessel design methods. The design of metal vessels is frequently based on primary membrane stresses only. Secondary discontinuity stresses, which are relieved by local yielding, are ignored. FRP materials are brittle and crack. Accordingly, discontinuity stresses must be considered.
- Design details. Attachment and other design details vary with the material of construction. For example, a nozzle in a filament wound vessel requires a very different design detail than a similar nozzle in a hand layup vessel.
- Corrosion. It is important to ensure that the correct plastic and glass are being used and that the process is being operated as designed. For example, small excursions in pH can have a serious effect on the corrosion performance of a material.
- Incorrect material design. The anisotropy of FRP must be considered.
- Fabrication quality.
- Transportation, handling, and installation.
- In-service abuse.
- Proof test. It is common practice to hydrostatically test new metal vessels to 150% of their design pressure. The over-pressure causes local yielding at discontinuities and relieves residual weld stresses. This results in a better state of stress during operation. Over-pressurization of an FRP vessel can result in local cracking at discontinuities.

The issues listed above were addressed by material suppliers, fabricators, users, and other interested parties. Considerable progress was made, but one major problem remained. Conventional NDT methods such as radiography, ultrasound, magnetic flux leakage, and eddy current were found to be unsatisfactory. Without a satisfactory NDT method for determining the structural adequacy of a vessel, FRP was not considered viable.

2.0 Initial Research

In late 1974, the author began discussions with a number of individuals that had experience with AE. The purpose was to explore use of the technique for testing FRP vessels. The response was not encouraging. Mr. Harold Dunegan was an exception. As in so many other cases with AE technology, development of a test procedure for FRP vessels can be traced back to his encouragement. His view was that there was very little information directly applicable to the issue, but thought that it might be possible to develop a field test. He recommended an exploratory test program to better understand the AE behavior of FRP.

In 1975, Monsanto began a two and a half year exploratory research program. The purpose was to assess the value of AE as a method for evaluating the structural integrity of FRP laminates. Also, it was hoped that the technology would give a better understanding of the micromechanics of the material under load. The research is summarized below.

Flexural tests were conducted by Dunegan/Endevco on two types of coupons fabricated with random fiber mat and sprayed chopped fiber. Particular interest was on count/time relationships, emission during hold, and amplitude distributions. The tests were conducted by Dr. Adrian Pollock and Mr. James Wadin whose experience and insight contributed to an understanding of the data. Complementary research by Dr. Pollock helped develop an understanding of wave propagation in FRP [2].

A test program conducted by McDonnell Aircraft was in two parts, laboratory tensile tests, and a field test of a full size vessel. The laboratory was state of the art and this permitted excellent control and instrumentation of the tests, and full data capture.

The field test served to assess the types of problems associated with field testing including: background noise, loading and load control, sensor mounting, safety, EMI, source location, fluid borne emission, and wave propagation through a large anisotropic structure. The flaw location system, which was based on time of arrival, was reported to be "totally ineffective". The following was included in the final report:

> *"The test shows that acoustic emission monitoring provides a viable method for evaluating structural integrity during proof testing of large cylindrical vessels. It was also clearly demonstrated that AE monitoring systems of greater sophistication will be required if AE is used as a criteria for qualification of the vessel for service."*

Tests were conducted at the Owens/Corning laboratory, which was designed for preparing and testing FRP test coupons. This proved to be a valuable capability. A range of representative FRP constructions were tested, primarily in flexure. At the time, Owens/Corning was a major supplier of filament wound vessels for underground storage of gasoline, which had an excellent performance record. This practical experience was an important contribution to the program. Monsanto provided the AE monitoring.

Monsanto conducted flexural tests and a test of a new vessel in a fabricator's shop. FRP constructions not fully covered by the other tests were examined and specific facets of AE behavior, such as the Felicity effect, were investigated. The purpose of the new vessel test was threefold: firstly, to explore difficulties in field testing, secondly, to evaluate the outline of a field test procedure and, thirdly, to qualify a new vessel for service.

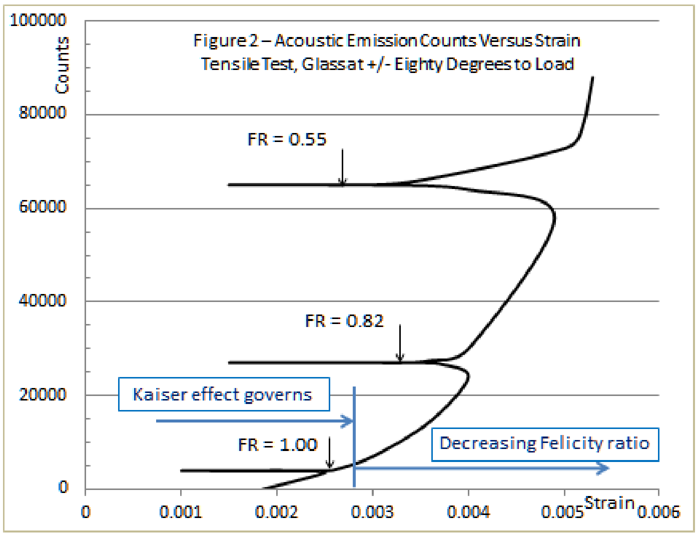
The 1974-77 research studies were very encouraging. At the outset, many AE experts opined that testing of FRP vessels was not feasible. By late 1977, investigators had an understanding of AE from FRP, a test program of different FRP constructions had been completed, and the outline of a field test procedure was being evaluated. The results of the research were reported at a session of the 1977 ASCE Fall Convention sponsored by the Structural Plastics Research Council [3][4]. The following was included in the paper:

> *"Acoustic emission testing of FRP structures is still in its infancy. The method, however, shows considerable promise as a non-destructive test to detect structural inadequacies. It is envisioned that FRP structures will be acoustically emission monitored during proof tests and at selected intervals thereafter."*

Laminates were found to emit copious amounts of emission. Investigators recommended focusing on the following AE parameters when determining the structural integrity of the vessel: Onset of emission, total emission, emission during load hold, high amplitude events, and the Felicity effect. The instrumentation available at the time precluded accurate source location and a zonal approach was recommended.

3.0 Felicity Effect

Figure 2 is a plot of cumulative emission counts versus applied strain. Loading is periodically interrupted with unload/reload cycles. The onset of emission during reload and the corresponding Felicity ratio are shown. Initially, the specimen exhibits the Kaiser effect. As load increases and the material suffers damage the Felicity effect becomes more marked. The test specimen was cut from the wall of a large cylindrical filament wound vessel and tested by McDonnell Aircraft. The 0.1 in. (0.25 cm) wound layer was overlaid by a 0.1 in. (0.25 cm) layer of chopped strand mat in a vinyl ester matrix. Load was applied parallel to what had been the axis of the vessel and the grips were designed to accommodate the curvature of the specimen and to apply the load in a manner that minimized bending. The glass fibers in the filament wound layer were 70% by weight and at +/-80^0 to the applied load. The glass content of the mat layer was 30% by weight. The specimen developed cracks along the continuous fibers. The figure illustrates that the Felicity effect is an indication of damage to the FRP. The Felicity effect depends on a number of factors including: load magnitude, rate of loading, and duration at different load levels. FRP is viscoelastic and this influences the behavior under load, and the recovery when unloaded.



The realization that the Felicity effect was an important parameter for testing of FRP came as a surprise. At the time, the Felicity effect was sometimes regarded as an anomaly and referred to as "The breakdown of the Kaiser effect." An important and significant portion of the research was devoted to understanding and quantifying the Felicity effect for the range of FRP materials used in vessels. The Kaiser effect has been referred to as a special case of the Felicity effect when the Felicity ratio is 1.0. The author believes that the Kaiser and Felicity effects are complementary to one another, and that each is important.

The term "Felicity effect" was first used in reference [3]. Felicity is the author's daughter. The author's employer did not object to publishing the research but, because it was not directly related to the Company's primary business, expected that the paper be prepared on the author's own time. Before computers, writing a paper involved a lot of cut and paste, copying, collating, and hand preparation of the figures. Felicity was a young girl and spent many weekend hours helping with the paper. When it came to describing the Felicity effect it was named after her in recognition of her contributions. The name gained acceptance when researchers from other organizations adopted the term.

4.0 CARP

The idea of forming a Committee on Acoustic Emission from Reinforced Plastics, to be known as CARP, emerged from a December 1977 meeting convened by Mr. John Teti at DuPont Engineering Center. CARP had a single purpose – to develop a draft procedure for AE testing of FRP vessels. The committee was officially known as the "Task Group on Acoustic Emission Testing of Reinforced Plastics." It was formed in 1978 and operated as part of the Reinforced Plastics/Composites Institute of the Society of the Plastics Industry.

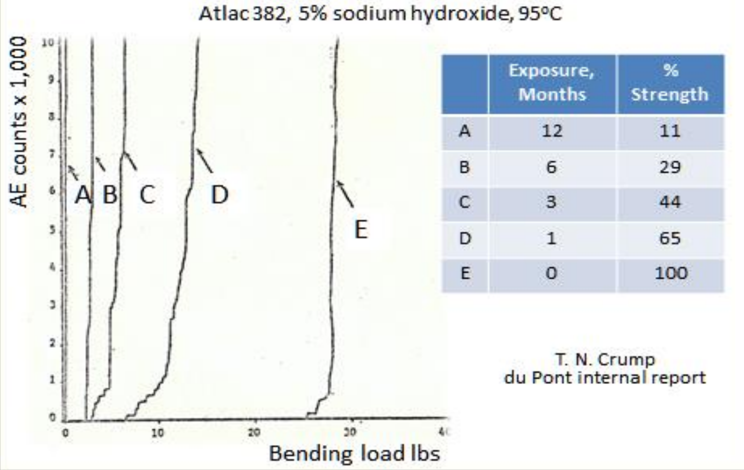
The author's 1977 paper [3] stimulated interest in the use of AE for testing FRP vessels. The DuPont meeting was attended by twenty-seven individuals from eleven organizations. The purpose of the meeting was to explore how to move forward to develop a practical and reliable NDT field test. The following organizations were represented:

Chemical Co. (Users)	*Research*	*Fabricators*	*Material Suppliers*
DuPont	Univ. of Delaware	An-Cor Industrial Plastics	Dow Chemical
Monsanto	Southwest Res. Inst.	Ceilcote	ICI Americas
Dow Chemical		Bettle/Justin Plastics	Owens/Corning Fiberglas
AE Equipment Suppliers			
Dunegan/Endevco			

The meeting began with a comprehensive review of NDT methods that were, or could be, used to test FRP. This was followed by reports of recent research. The use of AE emerged as an area of research that had considerable promise, although additional research and development would be needed to move the technology into the field. The participants recommended a joint program in which interested organizations would work together on complementary research and development. The matter was considered to be an urgent safety issue that should be given high priority.

Mr. Thomas Crump reported results of AE tests run at DuPont on corroded FRP samples. Figure 3 is taken from Mr. Crump's presentation. Flexural samples were soaked in 5% sodium hydroxide for periods of up to one year and then loaded in flexure with AE monitoring. The figure does not show the full range of counts on the vertical scale. The plots are labelled A through E corresponding to different exposure times and confirm that the AE data indicates the loss of strength. This is an important result, which confirms that the structural degradation of FRP by corrosion is readily detectable by AE.

Figure 3 – Acoustic Emission from Corroded FRP Samples
Atlac 382, 5% sodium hydroxide, 95°C



The United States has strict antitrust laws prohibiting competitors from working together. The FRP issue was considered of such importance to personnel safety that it was agreed to seek antitrust relief for a cooperative research and development program. DuPont addressed the legal issues, which were resolved in early 1978.

From spring 1978 until late 1981, CARP coordinated the research and development of the contributing organizations and provided a forum for the exchange of technical information. Approximately twenty-five organizations participated in CARP. These organizations included users of FRP vessels, fabricators, material suppliers, AE equipment manufacturers, universities, NDT test companies, and government laboratories. The programs coordinated by CARP were conducted by the participating organizations, rather than as funded research at universities or commercial laboratories. This had advantages and disadvantages. The primary advantage was that the research moved much faster. Also, with no contract there was flexibility to change direction and emphasis as new data became available. A disadvantage was the lack of the independent critical review that universities can provide.

5.0 Test Procedure, Field Testing, and Related Studies

CARP moved aggressively with focused complementary programs. The result was a change in emphasis. During the 1974-77 period, the purpose of the research had been to assess the value of AE for testing FRP. The new emphasis was on development of a field test procedure. During the period 1978-81, CARP held numerous working meetings. As needed, more formal meetings were held at which technical data were presented and discussed. The meetings allowed CARP members to assess gaps in knowledge and plan additional technical studies.

Two evaluation criteria emerged as particularly important for field testing. These were emission during load hold, and the Felicity effect. The loading procedure influences both of these criteria because of the viscoelasticity of the material. Two separate studies were carried out, one by Owens/Corning Fiberglas [5] and one by DuPont [6]. Tensile and flexural laboratory tests were run on a comprehensive range of different FRP constructions with emphasis on load holds, unload/reload cycles, and recovery. Large FRP objects were also tested, including beams, plates, and pipe. Evaluation criteria based on high amplitude events were an indication of strength loss due to glass fiber breakage. The count total and the rate of count increase are important as a field test warning of impending failure.

Instrument calibration, preamplifier gain, threshold settings, and resonant sensor frequencies were an early area of interest. Clearly, it was important that all CARP projects be on a comparable basis. The effect of teeing multiple sensors into a single channel was also investigated. An important improvement in field testing resulted from introduction by Physical Acoustics of the integral sensor. This combination of a sensor and fixed gain preamplifier into a single small casing, which could be glued directly to the vessel, had obvious practical benefits. More importantly, by eliminating the unshielded wire between the sensor and preamplifier, including frequency filters, and placing everything within a single shielded casing, went a long way to reducing the EMI and radio frequency interference encountered in early field tests. AE source location by the time-of-arrival method proved to be impractical for FRP. The high attenuation, background noise levels, and the variation of wave propagation properties with fiber orientation, were insurmountable problems. Instead, zonal location based on individual sensor activity was adopted. With this method, the AE test identifies a structural deficiency and provides an approximate location. Second and subsequent hit data may help refine the position of the emission source. Typically, follow-up visual examination is used to identify the defect.

An extensive field test program carried out by Monsanto helped develop the CARP procedure. In 1979, the Company lifted the prohibition on purchase of new FRP vessels, provided that all vessels pass an AE test as part of their acceptance. In 1980, a worldwide program was initiated to test all in-service FRP vessels. Over 500 vessels were tested, and approximately one third were replaced. The dramatic improvement in FRP performance as a result of this program can be seen in Figure 1. Catastrophic failures dropped from over two per year, to approximately one every four years. The 1982 failure was of a vessel that had been found to be deficient by an AE test and was being operated with special precautions while a new vessel was fabricated. The 1984 failure was more serious. The manager of a European plant elected to ignore company policy and waive the AE test requirement. The 1988 failure was a new vessel that was accidently over-pressurized during checkout, prior to the introduction of process fluids.

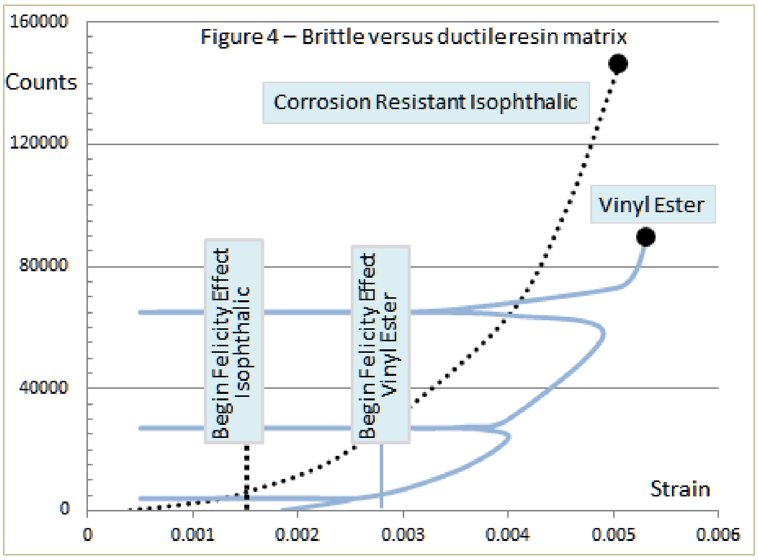
Most of the vessels tested by Monsanto operated at low pressure and were considered tanks. This was because the ASME Code governing construction of pressure vessels effectively excluded of one-of-a-kind FRP vessels. Texas was not governed by the ASME Code for FRP vessels and Dow Chemical had taken advantage of this exception. Through a careful design and a thorough quality control program, the company used FRP pressure vessels successfully. In order to evaluate design methods, Dow had scheduled a destructive test of a new vessel, 20 ft. (6.10 m) long and 42 in. (107 cm) diameter. It was decided to monitor the test with AE and share the data with CARP. Dunegan/Endevco, Owens/Corning Fiberglas, and Monsanto were invited to participate with Dow. Three AE systems were used to monitor the test. The test was also used to evaluate two other non-destructive test methods, strain gauge monitoring and dynamic pressure testing. Forty strain gauges were mounted on the vessel and pressure was applied by a proprietary pressurization system. The vessel was internally pressurized to failure, which occurred at 217 psi (1.50 MPa). Intermediate pressure holds and unload/reload cycles were included in the load schedule. The AE data were very important building blocks in development of the CARP procedure. A paper detailing the test was authored by Mr. Tom Hagemeier [7]. The following is excerpted from the paper:

> *"Although three methods of checking the vessel integrity were used during the test, only one indicated that it has potential use for non-destructive testing of FRP equipment. That one is acoustic emission. - - - - - Acoustic emission appears, at this time, to be the only means of proof testing FRP pressure vessels for their overall integrity and for field requalification applications."*

As experience was gained, it became apparent that a specific type of defect had a specific signature. It was observed that an inspector performing a field test was often able to guide the follow-up inspection and suggest the type of defect being sought. A number of organizations participated in a program to classify AE signatures of common defects [8].

At the beginning of the program, a group of inspectors with experience testing FRP vessels were asked to list the factors that helped them determine the type of defect present. These data were compared to the laboratory test results. Defects were introduced into plate samples reinforced with chopped strand mat. The following defects were tested: thin spots, voids, inclusions, crazing, star cracks, delamination, noncoupled secondary bond, and dry spots. Simulated defects give poor results, and only samples with genuine defects were evaluated. With a few minor exceptions, the laboratory test results were in general agreement with the inspectors' observations.

AE provided a better understanding of the micromechanics of FRP laminates. The ultimate strength values are governed by the glass reinforcement. The resin matrix has a relatively minor effect. It is known, however, that certain resins perform better than others. The better performing resins are often referred to as being "tougher". Research performed by Dow [9] showed that the strain corresponding to onset of the Felicity effect is considerably greater for some laminates than for others. Figure 4 shows counts against strain for two different laminates, one made with corrosion resistant isophthalic and one with vinyl ester. The vinyl ester data is the same as shown in Figure 2. The transition from Kaiser to Felicity effect was determined from a series of tests. Both laminates have similar ultimate strain but the strain at onset of the Felicity effect is very different. Damage in the corrosion resistant isophthalic begins much earlier. The difference is attributed to the ultimate strain of the pure resin, which is much greater for the vinyl ester.



The CARP procedure was intended for use by members of SPI. Even though it was later incorporated into national and international codes and standards, it was not written with this in mind. CARP members believed that it was important to keep the broader process industry FRP community informed of progress. Presentations were made to engineers, technicians, and inspectors within the members' organizations, and papers were presented at professional meetings likely to be attended by individuals that contribute to and use FRP vessels. Information was not published or presented at meetings of the AE community. An unforeseen consequence of this policy is that authors of review papers written many years later have overlooked the 1974-82 pioneering work on FRP composites.

With publication of the CARP procedure, the primary goal of the Task Force had been completed. As a follow-up, CARP organized a meeting to explain the procedure and present the studies that supported it. In response to the interest aroused by the CARP work, the scope of the meeting was expanded and became the First International Symposium on Acoustic Emission from Reinforced Plastics, which was held July 1983 in San Francisco.

References

[1] CARP/Adams, C. H., "*Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Tanks/Vessels*", 37th Annual Conf., Reinforced Plastics/Composites Institute, SPI, January 1982.

[2] Pollock, A. A. and Cook, W. J., *"Acoustic Emission Testing of Aerial Devices"*, Engineering and Operating Division Annual Conference, Southeastern Electric Exchange, 1976.

[3] Fowler, T. J., *"Acoustic Emission Testing of Fiber Reinforced Plastics"*, Preprint 3092, ASCE Fall Convention and Exhibit, San Francisco, 1977.

[4] Reference [3] republished in Journal of the Technical Councils of ASCE, Vol. 105, No. TC2, Dec. 1979.

[5] Fowler, T. J. and Gray, E., *"Development of an Acoustic Emission Test for FRP Equipment"*, Preprint 3583, ASCE Convention and Exposition, Boston, April 1979.

[6] Crump, T. N. and Droge, M. A., *"The Characterization of Fiberglass Reinforced Plastics Using Acoustic Emission"*, Managing Corrosion with Plastics – Vol. IV, NACE, 1979.

[7] Hagemeier, T. G., *"Monitoring of an FRP Pressure Vessel During Pressure Testing"*, Managing Corrosion with Plastics – Vol. IV, NACE, 1079.

[8] Scarpellini, R. S., Swanson, T. L. and Fowler, T. J., *"Acoustic Emission Signatures of RP Defects"*, First International Symposium on Acoustic Emission from Reinforced Plastics, Reinforced Plastics/Composites Institute, SPI , 1983.

[9] Cortez, A., Enos, J. H., Francis, E., Heck, H., *"Use of Acoustic Emission to Characterize Resin Performance in Laminates"*, First International Symposium on Acoustic Emission from Reinforced Plastics, Reinforced Plastics/Composites Institute, SPI, 1983.