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NONDESTRUCTIVE EVALUATION OF FIBERGLASS REINFORCED PLASTIC ROAD TANKERS SUBJECTED TO INTERNAL PRESSURES USING ACOUSTIC EMISSION MONITORING

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INTRODUCTION

The use of fiberglass reinforced plastics (FRP) in the fabrication of road tankers for the transportation of corrosive liquid products and wastes has the potential of growing considerably in coming years. The selection of the appropriate materials and the adequate mechanical design of such equipment can provide a total life-time cost which compares favourably with metallic tankers. Metallic tankers may either have to be made of relatively expensive alloys or else incorporate liners which may become expensive to properly maintain and/or replace over the years.

Because of the corrosive nature of its contents, it is common practice to use pressure to unload the tanker rather than to use pumping systems. The road tanker is not pressurized in transit, but while unloading it may be considered to be a pressure vessel given the typical unloading pressures in current use. This combination of hazardous contents and internal pressure loading makes the assured reliability of these tankers imperative.

Because of the very nature of polymer composites (such as FRP), the material and the structure are fabricated at the same time. Moreover, because a great proportion of the fabrication is done by manual methods, considerable variation can exist in the quality of tankers from different manufacturers or from the same manufacturer at different times. Adequate nondestructive means of quality control which are fast and inexpensive are required if FRP road tankers are to attain their potential.

One nondestructive testing method consists of Acoustic Emission (AE) monitoring of tankers subjected to internal pressure. The AE technique has the advantage of monitoring the tanker's response to typical loadings; thus, if there are flaws which may cause problems in actual use, they reveal their own presence. The method is relatively fast since it can give 100% coverage in real-time without requiring point-by-point scanning with sensors. A recommended practice which was first published in 1982 has become the source document which the ASTM and the ASME have adopted in their standards/codes.

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The source document, published by the Committee on Acoustic Emission from Reinforced Plastics (CARP), has been found incomplete and too restrictive for general application to all types of FRP tanker constructions. In particular, FRP tankers with balsa wood cores (BWC) routinely fail the CARP test although these tanker designs have proved adequate over more than a decade of service.

This paper describes the experience gained in more than 20 AE-monitored pressure tests. Eight of these tests were conducted to rupture. A new recommended test procedure is proposed based on the test results. The test consists of a fixed schedule of repeated pressure loadings, and the simultaneous measurement of the trend in AE activity. The tanker can easily be judged by the AE trend it exhibits, and it can be unambiguously accepted or rejected based on the criteria contained in the proposed procedure. While the new procedure is thought to be more general and less dependent on the experience of testing personnel, it does not replace the CARP practice, but may complement it in the testing of FRP pressure vessels such as these road tankers.

EXPERIMENTAL PROCEDURE

AE is the term which has become accepted to describe a class of phenomena which give rise to stress waves in solids. These phenomena are rapid transient material deformations. These transients, in the present context, are caused by stress redistributions in the composite structure when the polymer matrix cracks, when reinforcing fibers fracture, when delaminations grow, etc., as the structure is loaded. The stress waves propagate through the solid and are detected by sensors acoustically coupled to the surface of the structure. Contrary to more well-known NDT methods, the structure must be actually under load during the test. Thus, the loaded structure itself reveals the defects which are significant to its intended service conditions. To load the tankers, they are filled with water and pressurized using a water source at a sufficient pressure.

As the stress waves travel, they are modified by the material path. One important modification is the attenuation of the signal amplitude. The structure of the wall of a typical road tanker is shown in Figure 1. Figure 2 shows the attenuation in a tanker wall. A sufficiently dense packing of sensors is required to detect AE from all parts of the vessel. The tankers tested were 11 metres long and 1.8 metres in diameter and required sixteen sensors. Since amplitude attenuation is less serious for lower frequency signals this feature can be used to improve coverage of large structures. In general, twelve 150 kHz resonant sensors (HF) and four 60 kHz resonant sensors (LF) were used and located as shown in Figure 3.

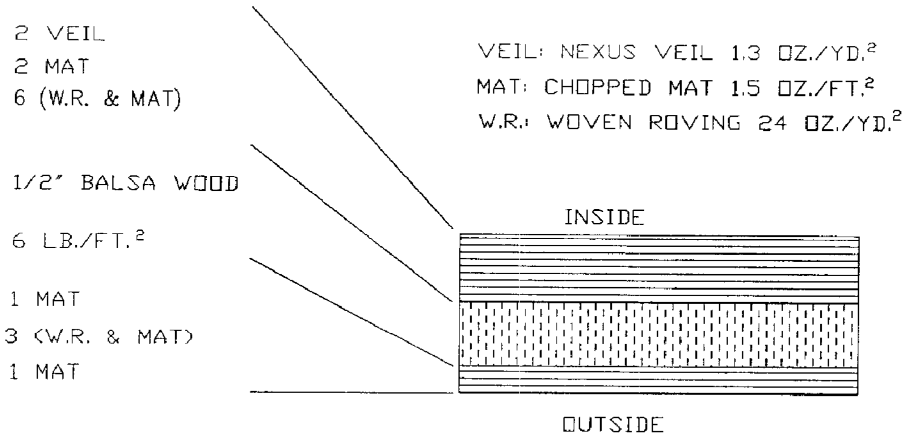

Figure 1. Wall construction of FRP/BWC road tanker.

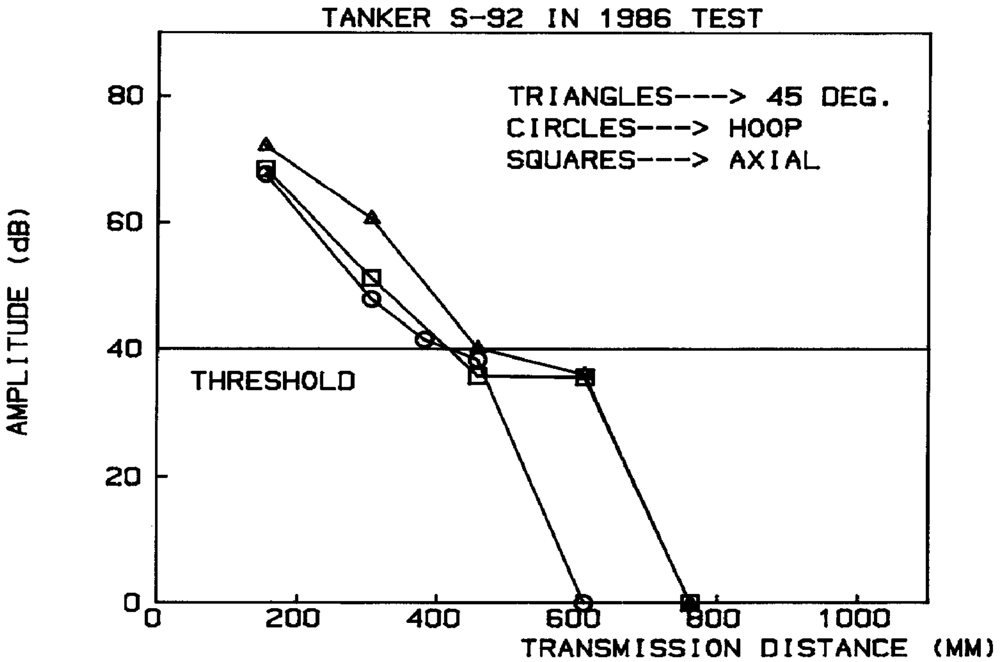

FIGURE 2. ATTENUATION OF HF SIGNALS BY FULL WATER TANKER.

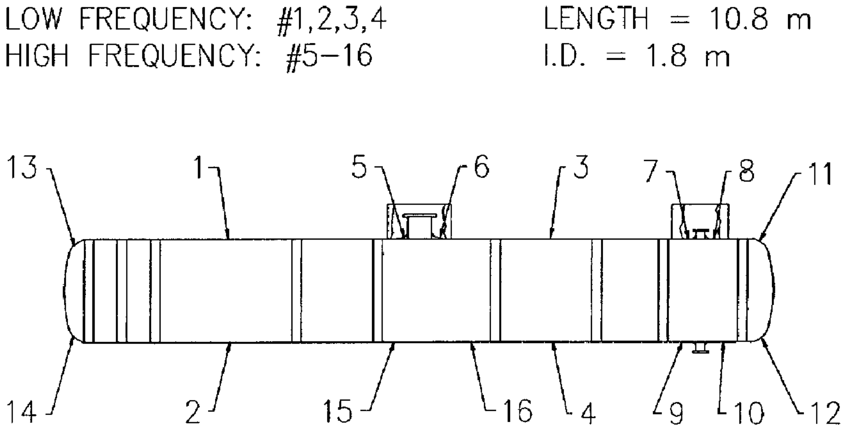

Figure 3. Sketch of typical FRP/BWC road tanker showing dimensions and sensor locations.

After the stress waves are detected by the piezoelectric sensors, the signals are amplified, filtered, analyzed, and results of the analysis are printed out. A simple set of parameters are sufficient for the purpose of this procedure. Figure 4 shows a signal and some common AE parameters. High and low thresholds were set to 70 dB and 40 dB, where 1 microvolt out of the sensor equals 0 dB. Signals were pre-amplified 40 dB in all cases. Table 1 is a listing of the AE instrumentation, and settings typically used.

TABLE 1.
AE instrumentation and settings typically used to test the FRP/BWC road tankers.

AE Analyzer	PAC Atlas 7016, sn. 111
12 transducers 4 transducers	PAC R15I, 150 kHz resonant, w/40 dB preamp PAC R15I, 60 kHz resonant, w/40 dB preamp
High threshold Low threshold	70 dB w.r.t. 1 microvolt at sensor = 0 dB 40 dB w.r.t. 1 microvolt at sensor = 0 dB
High frequency Low frequency	100-200 kHz bandpass filter 20-100 kHz bandpass filter
Dead time *	100 microseconds

* Two events ocurring less than 100 microseconds apart will not be resolved as separate events.

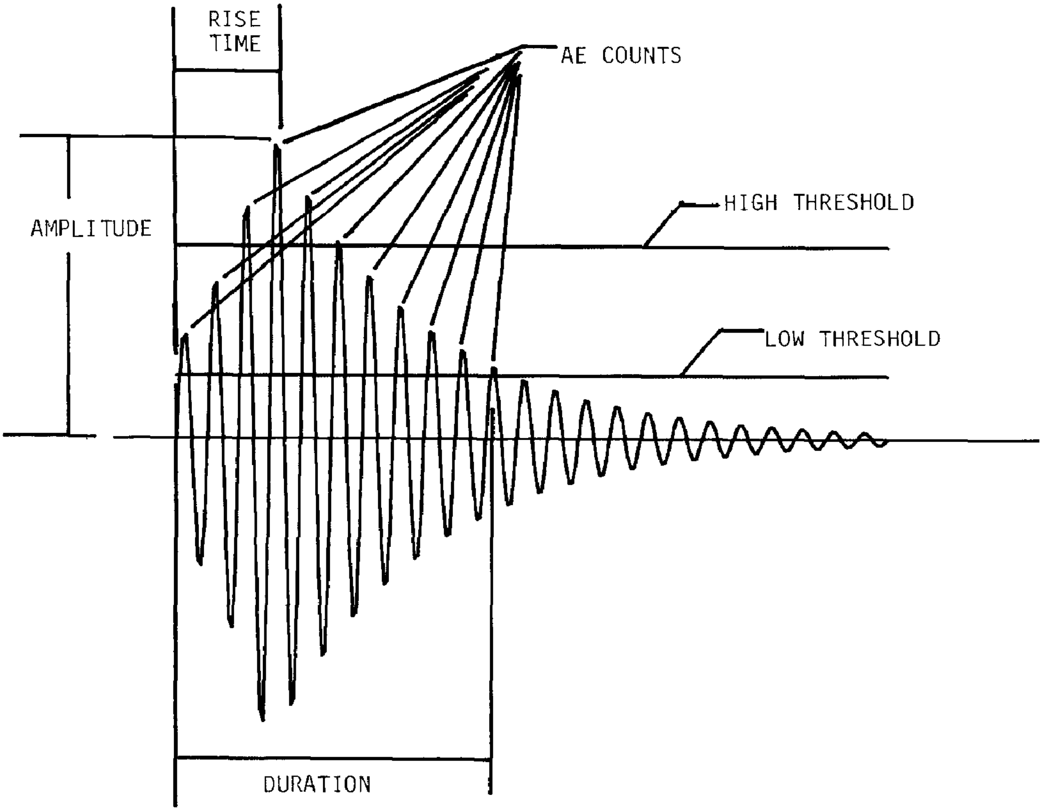

Figure 4. Schematic representation of a signal from one high threshold AE event showing various characteristics of the signal.

Because it is intended for general industrial field use, it is necessary to monitor the installed AE system for false AE due to ambient conditions (pump noise, water turbulence, electrical interference, rain, etc.). During a test, such noise must be completely eliminated or else must be discounted in the data reduction phase.

RESULTS

The first FRP/BWC tankers were tested in 1985. Initially, the CARP recommended practice (ref. 1) was used. (In July 1989, this practice was adopted by the ASME for the nondestructive acceptance testing of Class II FRP pressure vessels.) Figure 5 shows the pressure schedule for the testing procedure.(ref. 2) This recommended practice accepts or rejects FRP pressure vessels based on several criteria:

1. Total HF AE counts must be below a measured number Nc; Nc is normally about 5 000;
2. AE activity must stop during the constant-pressure hold periods;
3. The Felicity ratio must be greater than 0.95; this ratio is obtained by dividing the stress at which "significant" AE activity is recorded by the highest stress previously attained;
4. The number of AE events above the high threshold must be less than 10.

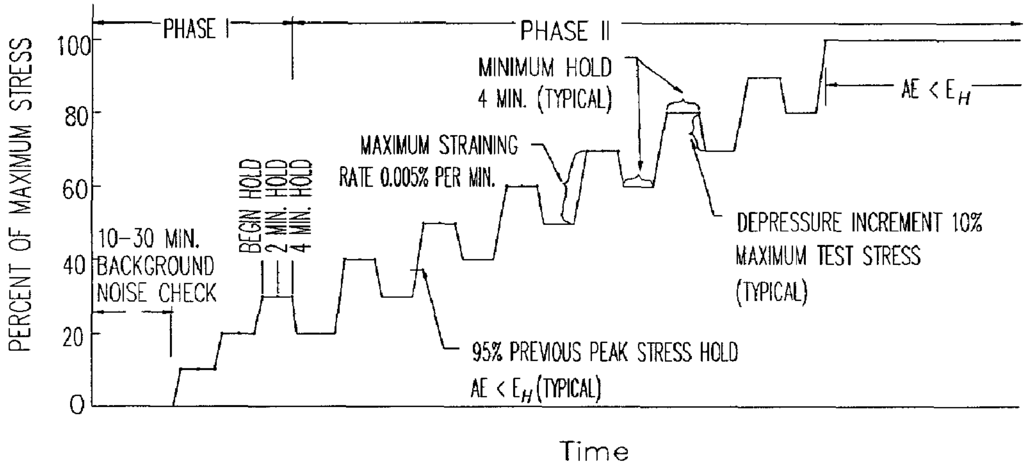

FIGURE 5. LOADING SCHEDULE RECOMMENDED BY CARP FOR FRP PRESSURE VESSEL TESTING.

The tankers tested failed all the criteria. Table 2 gives AE count data for tests of four new FRP/BWC tankers tested in autumn 1987. Not only are the numbers much higher than Nc, but they vary considerably from one unit to another.

TABLE 2.
Cumulative AE activity for four new FRP/BWC road tankers using the CARP recommended loading schedule.

	TANKER S-106	TANKER S-107	TANKER S-108	TANKER S-109
NHF	1 263 753	1 099 109	228 420	754 645
NLF	104 533	211 008	37 290	101 983
EHFHT	491	699	112	483

Tankers such as those mentioned above had been in active service for many years and had proven satisfactory; yet they all failed the CARP criteria.

Either the particular tankers tested were truly defective, or the CARP procedure was not immediately applicable to such tankers. Another set of acceptance criteria might then have to be developed.

During the first year of testing, one characteristic AE behaviour was noted: the AE activity during the second and subsequent pressure cycles was considerably less than during the first cycle. The HF data from Table 2 is plotted in Figure 6 using an AE parameter Y which is calculated by dividing the AE counts by pressure. Several pressurization cycles were run; these

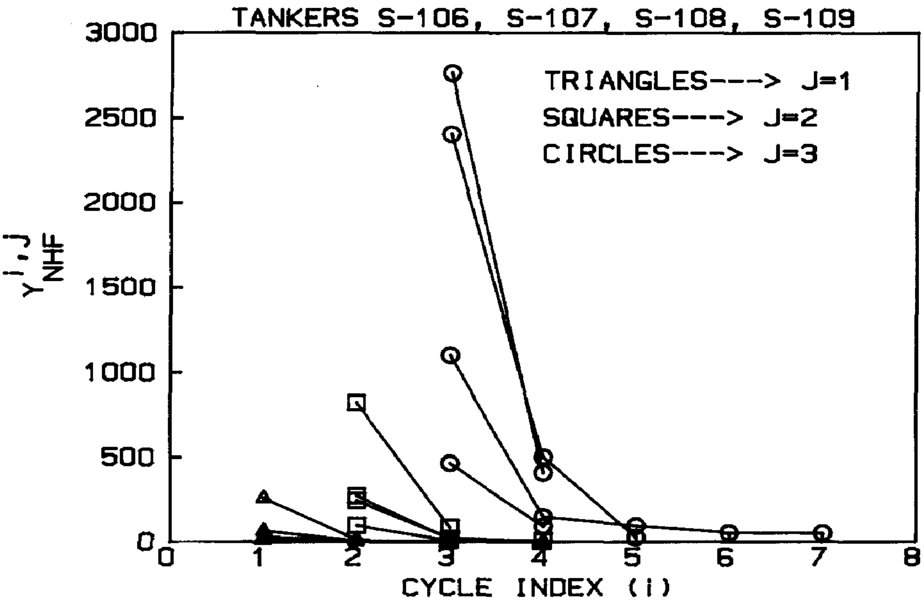

FIGURE 6. AE PARAMETER Y FOR FOUR NEW FRP/BWC TANKERS. J=1 IS 140, J=2 IS 280, J=3 IS 420 kPa. Y VALUES SHOW CONSIDERABLE VARIATION FOR NOMINALLY IDENTICAL TANKERS.

cycles are denoted by the superscript "i". The three pressure values used were 140 kPa, 280 kPa, and 420 kPa, denoted with superscript j=1, j=2, and j=3, respectively. The scatter in the data, especially at 420 kPa is caused by the variation from tanker to tanker. Since our working hypothesis was that the trend of AE activity rather than the absolute number of AE counts revealed the quality of these FRP/BWC tankers, a better data presentation results when AE counts are normalized with respect to activity ocurring during the first cycle. Such a plot is shown in Figure 7 for new tanker S-113 and in Figure 8 for tanker S-74 which had been in service for four years. Three AE parameters are plotted in these three last figures: NHF is total high frequency AE counts, NLF is total low frequency AE counts, and EHFHT is total high frequency AE events above the high threshold. The trend is the same for all three parameters, and it is the same for both the new and the used tanker.

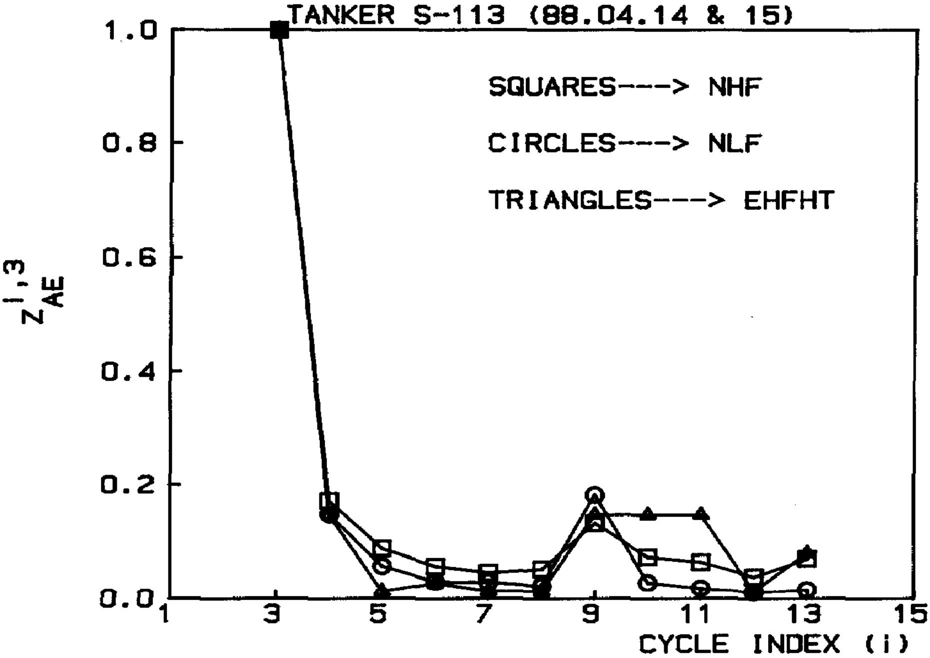

FIGURE 7. AE PARAMETER Z FOR THE THIRD PRESSURE RANGE.

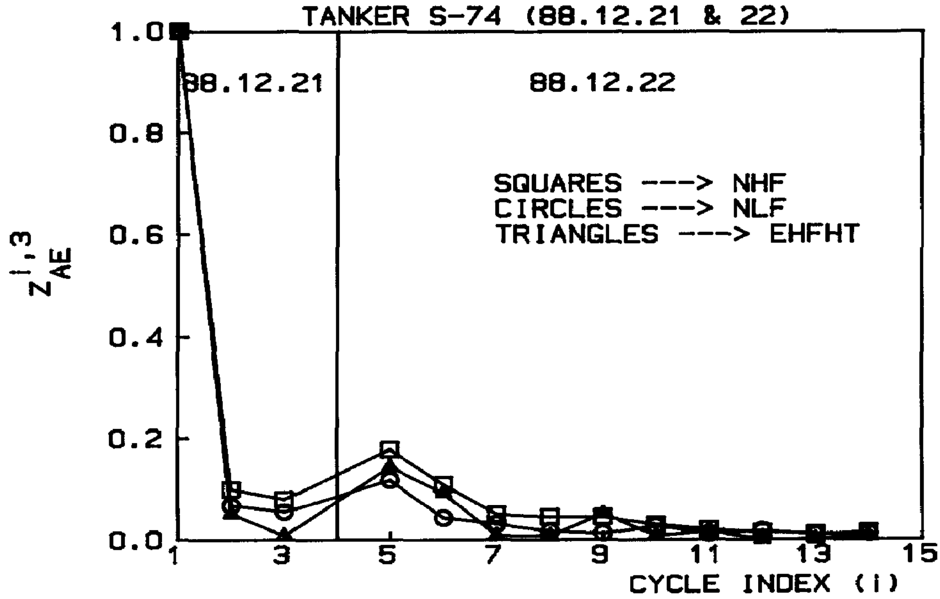

FIGURE 8. ACTIVITY TREND IS EVIDENT FOR THIS "GOOD" FOUR YEAR OLD FRP/BWC TANKER TESTED AT 420 kPa. THE INCREASE AT CYCLE 5 IS DUE TO AN OVERNIGHT INTERRUPTION OF THE TEST.

This suggests that the use of one parameter only should be sufficient for the routine test procedure. Since AE counts are weighted by the event amplitudes, and these amplitudes are related to damage severity, AE counts are more informative than AE events. Furthermore, since a large structure like a tanker might have "good" areas and "bad" areas, it is necessary to determine the AE activity trend at each location. Otherwise, data from a local "bad" area might be lost in global "good" results. With these considerations in mind, a proposed procedure for testing FRP/BWC tankers was recommended (ref. 3). Figure 9 shows the pressurization schedule for the acceptance test. The suggested data tabulation is given in Table 3 from an actual test. Only data from cycles numbered 3 to 6 can be used to accept the tanker.

TABLE 3.
Recommended format for acceptance/rejection decision table, showing a full data-set from an actual tanker test at the test pressure of 1.5 times the design pressure. Data includes AE activity during the hold periods. AE trend numbers must be truncated to one decimal place before evaluating the results.

CH.	CYCLE #3		CYCLE #4		CYCLE #5		CYCLE #6	
#	ΣNLT	Z	ΣNLT	Z	ΣNLT	Z	ΣNLT	Z
1	38 980	1.00	2 345	0.06	609	0.02	250	0.01
2	24 510	1.00	3 090	0.13	346	0.01	705	0.03
3	56 600	1.00	3 604	0.06	411	0.01	1 236	0.02
4	13 668	1.00	851	0.06	303	0.02	298	0.02
5	37 015	1.00	4 035	0.11	663	0.02	257	0.01
6	25 670	1.00	5 202	0.20	1 114	0.04	582	0.02
7	37 396	1.00	2 004	0.05	889	0.02	257	0.01
8	19 705	1.00	2 616	0.13	702	0.04	607	0.04
9	17 947	1.00	2 208	0.12	1 136	0.06	379	0.02
10	71 558	1.00	2 921	0.04	495	0.01	395	0.01
11	8 597	1.00	1 117	0.13	154	0.02	119	0.01
12	42 995	1.00	2 680	0.06	657	0.02	200	0.01
13	2 558	1.00	192	0.08	133	0.05	32	0.01
14	6 277	1.00	505	0.08	198	0.03	119	0.02
15	4 403	1.00	210	0.05	37	0.01	64	0.02
16	12 101	1.00	932	0.08	78	0.01	86	0.01
Σ*	419 990	1.00	34 512	0.08	7 925	0.02	5 779	0.01

* This is LF and HF AE counts above 40 dB summed over all 16 channels used.

The AE trend data acquired must be interpreted with respect to AE trends presented by "bad" tankers, or tankers which are near their failure point. Burst tests are needed to establish these "bad" trends. Only a limited number of burst tests could be conducted during the project because of the cost/availability of tankers. Among these burst tests, two were performed

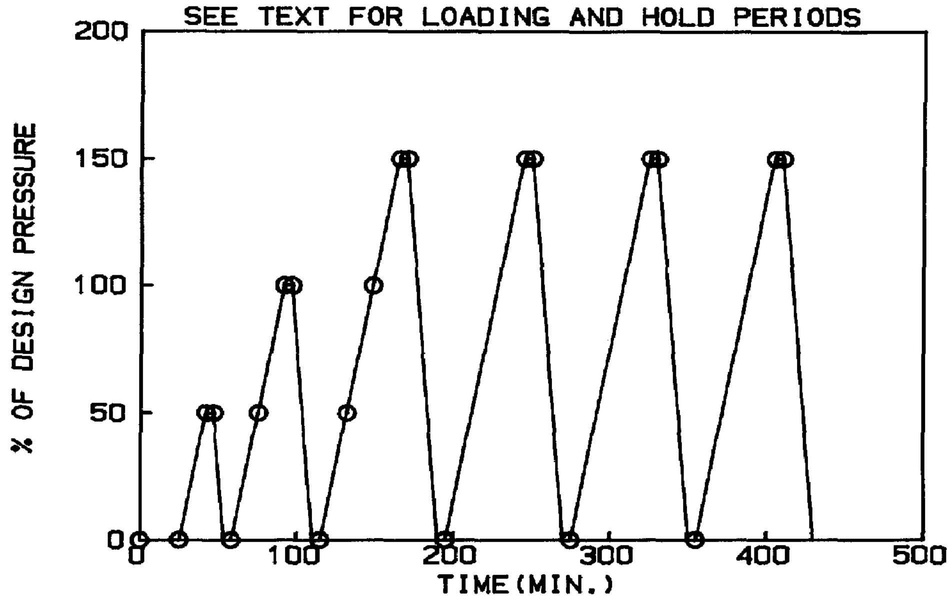

FIGURE 9. THE RECOMMENDED LOADING SCHEDULE CONSISTS OF 6 CYCLES, THE 4 LAST BEING RUN UP TO THE TEST PRESSURE. DATA IS RECORDED AT 22 POINTS.

using the recommended schedule (Figure 9). For these two tankers (S-37 and S-40), a margin of safety can be calculated. Table 4 shows the results for the two burst tests as well as for two acceptance tests performed on new tankers using the proposed procedure.

TABLE 4.
List of tankers amenable to exact application of proposed practice.

TANKER #	PRESSURE	DECISION	SAFETY MARGIN
S-37	420 kPa 504 kPa 588 kPa 789 kPA	ACCEPTED ACCEPTED REJECTED BURST	1.3
S-121	420 kPa	ACCEPTED	
S-122	420 kPa	ACCEPTED	
S-40	220 kPa 280 kPa 336 kPa 392 kPa 420 kPa 756 kPa	ACCEPTED ACCEPTED ACCEPTED ACCEPTED REJECTED BURST	1.9

Based on the results of burst tests and on data from the tests on new, presumably good tankers, a new criterion based on AE trend was proposed. In short, a tanker must be tested using the pressure schedule in Figure 9, and the data recorded both on a global and a local level. After all extraneous noise is eliminated, the data is tabulated as in Table 3. If the Z parameter falls below 0.2 for all the sensors by cycle #6 the tanker is accepted. Otherwise, it is rejected. This was the basis for the decisions in Table 4.

More testing is needed to establish the relation between current AE trend behaviour and current margin of safety, and that between current margin of safety and the recommended time until the next quality acceptance test.

CONCLUSION

Acceptance testing of FRP/BWC road tankers using AE monitoring during hydrostatic pressure tests could be an effective method to promote safe and wider use of these structures. Existing AE procedures do not appear well adapted to this end.

A new AE testing procedure was developed which relies on the trend of AE activity during repeated loading rather than on several absolute numerical limits to establish the fitness-for-service of these tankers. While the present authors consider that the proposed procedure might have general applicability for composite structures, it is prudent for the time being to limit the scope of the test to FRP/BWC tankers, given the limited data base.

The proposed procedure permits rapid unambiguous acceptance decisions to be made, and does not place great burdens on the experience and subjective reactions of test personnel. It is less likely to result in false rejection of good equipment, and incorporates useful features of existing procedures.

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Journal of Acoustic Emission, 9(1), 1990.

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