Acoustic emission monitoring of composite containment systems

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Abstract. This paper considers two different types of composite containment system, and two different types of acoustic emission (AE) monitoring approach. The first system is a composite reinforced pressure vessel (CRPV) which is monitored both during construction and in-service using a broadband modal acoustic emission (MAE) technique. The second system is a membrane cargo containment system which is monitored using both a global as well as a local AE technique. For the CRPV, the damage assessment is concerned mainly with the integrity of the composite outer layer at the construction stage, and possible fatigue cracking of the inner steel liner at the in-service stage. For the membrane tank, the damage assessment is concerned with locating and quantifying any abnormal porosities that might develop in-service. By comparing and contrasting the different types of structural system and different monitoring approaches inferences are drawn as to what role AE monitoring could take in the damage assessment of other types of composite containment system. (Detailed technical data have not been included, due to client confidentiality constraints.)

Introduction
Lloyd’s Register EMEA (LR) carry out a wide range of independent safety assessments, as part of our wider role as Classification and Certification Authority. This involves us with independent analyses, inspection, testing and measurement, throughout the lifecycle of design, construction and in-service operation. This paper considers two scenarios, involving composite containment systems, which are of growing interest across a range of industries.

Scenario 1 - Composite Reinforced Pressure Vessels (CRPVs) in ships
LR are involved with marine projects to transport compressed natural gas (CNG) in cylindrical pressure vessels, of diameter circa 40 inch and lengths up to 80 foot. The steel cylinders are overwrapped with a fibre reinforced plastic (FRP) composite material. A process known as “autofrettage” is used during construction such that the composite overwrap is used to induce residual compressive stresses within the steel cylinder, to improve in-service performance. Some general arrangement images are shown in Figures 1 and 2.

Figure 1. Cutaway concept view of CRPVs in CNG ship.
There is an LR safety requirement that an in-service inspection and testing plan be developed and approved for the CRPVs. It has been established that it is not considered appropriate to consider the in-service inspection and testing in isolation, as it is necessary to additionally link in to elements from:
- the inspection and testing carried out during manufacturing;
- the construction quality assurance (CQA) and quality control (QC) procedures, and also:
- the underlying design approach.
In other words the approach to the complete lifecycle of design, construction (manufacture at works and installation in ship) and operation (in-service) needed to be considered together.

**Philosophy for design, construction and operation of CRPVs**

In essence, once the CPRVs are installed within the CNG carriers they become extremely difficult to inspect and test in service. As a consequence the overall design philosophy has been to:
- design with conservative margins of safety, and a “leak-before-break” philosophy ;
- construct under a strict QA and QC regime, including use of LR approved materials;
- inspect and test thoroughly at the construction stage (100% coverage);
- inspect and test as far as reasonably practical, in-service.

The in-service inspection and testing proposals include:
- regular visual inspection, as far as reasonably practical;
- regular monitoring of vessel pressure and temperature by the crew;
- having in place a continuous monitoring system to detect and signal leaks, such that any leaking CRPV can be safely taken out of service before compromising safety;
- periodic pressure testing, using air (as hydrotesting is impractical in service);
- periodic acoustic emission testing (AT), focussing on the three areas identified as being most at risk from fatigue cracking, namely the circumferential welds at the centres of the CRPVs, the longitudinal seam welds, and in the vicinity of the nozzles at the extremities of each CRPV.

In respect of acoustic emission testing (AT), this is an established technique for testing at the construction stage, in relation to the composite outer layer of the CRPV. However it is less well established as a technique for testing the steel cylindrical liner at the in-service stage, in relation to fatigue cracking in the CRPVs, and hence in this respect it was only to be regarded as an additional safeguard, which might give early warning of abnormal problems, but which was not relied upon in terms of the “safety case” that the operator was putting forward to the Classification Society (LR).
LR does not have in place any detailed Rules relating to CRPVs within CNG carriers, although LR do have in place more general requirements in respect of inspection and testing, both in-service and at prior stages. With this in mind it was necessary to revert to a “first principles” type of approach, to the in-service inspection and testing as a whole, and in particular to the acoustic emission testing (AT) element.

In essence the in-service inspection and testing requirement involves:
- continuous monitoring of the CRPVs onboard;
- continuous monitoring of the environment surrounding the CRPVs onboard;
- periodical survey in accordance with the LR regulations for gas carriers, which include:
  (a) annual survey;
  (b) intermediate survey (held with or between the 2nd and 3rd annual survey);
  (c) special survey (5 years);
  (d) alternate special survey (from 10 years) – pneumatic (air) test, as opposed to hydrotest, in view of the inability to hydrotest in-service;
  (e) periodic acoustic emission testing (AT) of the circumferential welds, seam welds and end nozzles.

A detailed plan for meeting these survey requirements was needed, once the “high level” philosophy and plan had been reviewed and approved by the Classification Society (LR). As well as possible fatigue cracking, to be monitored by the AT system, corrosion aspects were also needed to be addressed. In respect of the in-service AT, this part of the overall approach needed to be further established and documented, and this was conducted as a separate activity, and reviewed separately by technical specialists from within the Classification Society (LR).

Possible fatigue cracking during operations and the role of acoustic emissions testing (AT) during the in-service stage

The design codes applicable to the CRPVs required that that the likelihood of fatigue failure occurring (in service) was to be sufficiently low, and that even if a crack penetrating the wall of the steel liner were to occur then the subsequent leakage would be detected rapidly and controlled, by taking the particular CRPV out of service at the next unloading docking.

The system designer considered the case of a small defect in the steel liner, of the maximum size which could escape detection by conventional non-destructive examination (NDE), and whether or not this defect would propagate through the thickness of the liner (20 mm) within the anticipated ship life. The initial defect considered was of the order of 1.5 mm, and the critical size was taken as one quarter of the liner thickness, namely $\frac{1}{4} \times 20 = 5$ mm, in line with the applicable design code (ASME) and the “leak before break” philosophy. Calculations showed that, over the ship life (20 years x 100 load/unload cycles per year = 2000 cycles) and under the environmental and other operational conditions assumed, the initial crack was unlikely to grow to anywhere near critical size. Moreover, in view of the predicted stress intensity levels in the liner and liner welds, and the relatively low number of load/unload cycles (2000), the postulated 1.5 mm initial defect was likely to grow so slowly that it might well be undetectable by periodic (annual) acoustic emission monitoring, even if the periodic test covered a large number of load/unload cycles. The purpose of the in-service AT was therefore NOT to monitor “normal” fatigue crack growth, which could be considered as “slow/realistic”, but was added in as an extra safeguard, in case of “abnormally high” (or “rapid/pessimistic”) fatigue crack growth, which might occur for unknown reasons. The in-service AT was therefore not being relied upon in the “safety case” being made for the CNG carriers, but was part of the overall operator desire for a “best possible programme”.
Modal acoustic emission (MAE)

Modal acoustic emission (MAE) is a relatively new non-destructive testing (NDT) method which represents the latest development in the field of acoustic emission. MAE determines the types of acoustic emission sources in plates, rods, shells, and other thin-walled (up to about 2 inches thick) materials using the shape of the wave mode rather than just counting events with traditional technology. The basic concepts of how MAE identifies crack growth are:

- extensional wave modes, coupled with a high frequency content, are diagnostically indicative of crack growth;
- comparison of the extensional and flexural wave modes indicates the depth of a crack;
- association of an event with a given point in the pressure cycle indicates crack opening, growth, and crack closing;
- repeated events that occur at high stress at the same location are significant;
- comparison of observed wave forms with those predicted by theory.

A summary of MAE, in relation to composite pressure vessels, is contained in Reference 1. More general details are given by commercial test organisations such as (for example) Digital Wave Corporation - see their web site www.digitalwavecorp.com for further details of MAE.

Scenario 2 - LNG ship cargo containment systems (CCS)

LR are involved with many marine projects to transport, store and process liquefied natural gas (LNG) in cargo containment systems (CCS). There are a number of different types of CCS, including membrane, MOSS and SPB. With respect to the membrane type, the predominant systems are designated NO96, Mk III and CS1, general descriptions being available from the designer, Gas Transport and Technigaz (GTT) from their web site www.gtt.fr. The particular CCS of interest here is the Mk III type (see Figure 3), and the particular area of interest is the secondary barrier. To assess the in-service condition there are a number of different test types available:

- pre-docking/at sea, Low Differential Pressure Test (LDPT) – References 2 and 3;
- during docking/alongside, Secondary Barrier Tightness Test (SBTT) – Reference 4; global AE (acoustic emission) and local AE – Reference 5.

These different but complimentary test types will now be briefly reviewed, with fuller consideration given to global and local AE.

Figure 3. Cargo tank arrangement.
Primary Insulation also known as Inter-Barrier Space (IBS).
Secondary Insulation also known as Insulation Space (IS).
**Low Differential Pressure Test (LDPT)**

The membrane tank is non-self supporting and consists of a very thin layer or membrane (primary barrier) that derives its support from the adjacent hull structure via the interconnecting insulation material. The primary barrier is in contact with the cargo. Membrane containment systems must always be provided with a secondary barrier to ensure the integrity of the total system in the event of primary barrier leakage. The secondary barriers on Mk III (and CS1) ships are made from a composite material – triplex – which is, by nature, liquid tight but not necessarily 100% gas tight.

The space between the primary barrier and the secondary barrier is known as the inter barrier space (IBS) or the primary space. The space between the secondary barrier and the hull structure is called the insulation space (IS) or secondary space (Figure 3).

The International Code for the Construction and Equipment of Ships carrying Liquefied Gasses in Bulk (or put more simply – the IGC Code) requires the secondary barrier of the Mk III LNG Cargo Containment System to be periodically checked for its effectiveness using an appropriate method. The current recognised method for doing this is to carry out a Secondary Barrier Tightness Test (SBTT). This test involves the application of a relatively “high” differential pressure across the secondary barrier through the application of a partial vacuum to the insulation space. SBTT can be carried out when the vessel is gas free and alongside, or in dry-dock, or if the vessel is at anchorage within protected waters.

Encouraged by Lloyd’s Register, Samsung Heavy Industries (SHI) and GazTransport & Technigaz (GTT) have collaborated in developing a new approach to monitoring the effectiveness of the secondary barrier. This procedure, called Low Differential Pressure Testing (LDPT), can be carried out while the vessel is operating (unladen) and therefore allows more frequent monitoring of the barrier membrane tightness. LDPT consists of two tests, which involve the application of relatively “low” differential pressure across the secondary barrier:

- LPDT-A checks for barrier membrane porosity from the IBS to the IS;
- LPDT-B checks for barrier membrane porosity from the IS to the IBS.

It is possible to detect some external leaks (not due to the integrity of the membranes but due to other outfitting) during the stabilization phase of LDPT-A. For this reason LDPT-A should be carried out prior to LDBT-B. Diagrams illustrating LDPT-A and LDPT-B are shown in Figures 4 and 5 below.

![Figure 4. LDPT-A Pressure vs time.](image-url)
Secondary Barrier Tightness Test (SBTT)

The Secondary Barrier Tightness Test (SBTT) is a critical part of the classification approval process and the test protocol is often agreed in advance of the docking, to avoid delays and adverse confrontations during the docking. The SBTT can be carried out when the cargo tanks are gas free and the vessel is alongside, or in dry-dock, or at anchorage in protected waters. Such testing normally forms part of the of the ship’s Special Survey (every 5 years, on average).

The SBTT is carried out by establishing a “high” differential pressure across the secondary barrier. The test supplies the data, which gives information about the global porosity of the secondary barrier of each cargo tank. The data obtained from the first test before delivery will be used as the benchmark for comparison with subsequent test results during the ship’s life. In order to obtain test results that can be compared to the benchmark values the test conditions must be standardised, matching the conditions under which the benchmark data was obtained.

The SBTT starts with the inter-barrier space (IBS) open to atmosphere and the insulation space (IS) isolated and stabilized at a partial vacuum. The IBS is maintained at atmospheric pressure, while keeping the IS isolated and free to increase towards the IBS pressure (Figure 6). Any porosity of the secondary barrier would be from the IBS to the IS. (This is important because if the differential pressure were reversed, this could result in damage to the secondary barrier bonding).

Figure 5. LDPT-B Pressure vs time.

Figure 6. SBTT. IS pressure vs time.
The IS pressure is then monitored to determine the vacuum decay rate (VDR). At new build, typical VDR would be expected to be not exceeding (and normally much lower than) 45mbar/hr. The VDR is then used to agree what further action is required. Depending on what VDR is yielded by the SBTT further action may include all or some of the following:

- a controlled hearing test (Reference 5);
- global acoustic emission (AE) mapping (Reference 5);
- localised AE mapping (described below).

Post docking, if the actual VDR is found to be greater than an agreed figure, when the vessel is afloat, LDPT should be carried out for reference purposes. This would be:

- in preparation for subsequent in-service secondary barrier monitoring;
- to check the IBS and IS could be maintained at the design differential pressure and therefore providing effective independent leak detection systems.

Possible reasons for larger than expected vacuum decay rate

Vacuum decay rate (VDR) is affected by normal and abnormal porosity of the secondary barrier (SB). Normal porosity of the SB contributes to the overall VDR but will not lead to liquid entering the insulation space (IS) in case of flooding of the IBS. Normal porosity cannot be detected through hearing (audible) tests or acoustic emission (AE) measurements. On the other hand, abnormal porosity (such as indications resulting from glue debonding) can be detected through hearing tests and AE measurements.

Global acoustic emission (AE) measurements

When VDRs yielded by SBTT indicate further investigations should be undertaken a hearing test is first carried out. The hearing test should be carried out when the ship is otherwise “quiet”, and ideally over a period of time to encompass a range of differential pressures. Global AE measurements are then undertaken in order to confirm the location of the hearing indications and detect any other indications that have not been detected by the hearing test.

A secondary barrier membrane with abnormal porosity will produce acoustic emissions when subjected to a differential pressure. The principal of AE measurement is to detect and locate the position of the defect by measuring and mapping the AEs. To do this, global AE measurements are carried out by first installing low frequency acoustic probes (approximately 10 to 100kHz broadband range, often 30 to 100 kHz) inside the cargo tank and/or outside in way of the double hull (ballast, cofferdam and trunk deck spaces). The probes are installed in a matrix pattern. The background noise is measured for calibration purposes and then a differential pressure is applied across the secondary barrier. The procedure is similar to that used for SBTT in that the IBS is maintained at atmospheric pressure and the IS isolated and stabilized at a partial vacuum. The IBS is maintained at atmospheric pressure, while keeping the IS isolated and free to increase towards the IBS pressure. Recording of the global AE measurements is carried out while the IS pressure is rising towards the IBS pressure. Other sources of noise should be kept to a minimum during this phase. For confirmation of an indication or more precise mapping of an indication the spacing between the probes may be reduced.

Based on experience from vessels of the same class using established global AE procedures an extended Special Survey docking might be required, if repairs are found to be necessary. The recent introduction of localised AE measurements can contribute significantly in reducing such periods. A time saving during docking is clearly of interest to many parties.
**Localised acoustic emission (AE) measurements**

Localised AE measurements can be divided into two main regions of activity:
- liquid dome (upper part of cargo tank, above liquid level);
- cargo tank walls (lower parts of cargo tank, exposed to liquid).

Global AE is usually first carried out on the liquid dome followed subsequently by the cargo tank walls. When global AE measurements have been completed on the liquid dome, localised AE can be carried out on the liquid dome in parallel with global AE measurements being carried out on the rest of the cargo tank.

Localised AE mapping has been carried out by LR Technical Investigations (TID) in regions where indications have been detected by global AE. In general the localised AE mapping has more precisely located each indication and reduced the amount of excavation necessary to expose the defect. As a result the extent and number of repairs have been able to be minimised and the ship returned to service as quickly as possible. The measurements have also assisted in quantifying each indication in terms of its contribution to the VDR as a whole.

Localised AE should be undertaken during “quiet” times (e.g. at night, when “noisy” operations on board are minimal; but during daytime is possible), and when the associated tank IS is under partial vacuum, typically with a differential pressure between the IS and IBS of ~500 mbar. Localised AE can therefore be undertaken during the period when the differential pressure is stabilised subsequent to completing the initial global AE measurements on the tank walls. An example variation of insulation space pressure against time is shown in **Figure 7**.

![Figure 7](image)

**Figure 7.** Insulation Space pressure vs Time.
Example cycle when both global and local AE are required.

TID portable equipment (**Figure 8**) is used to carry out localised AE measurements on the outside, and inside as far as possible, of the liquid dome area, and elsewhere if desired.
Microsoft Excel™ is used to create local AE mapping of areas with AE values greater than a predetermined threshold. The AE measurements are entered into an Excel table, factored as appropriate, and then plotted using the Excel™ internal graphing facility. An example is shown in Figure 9.

From the local AE mapping, the cargo tank construction drawings, and previous experience, it is possible to estimate the zone of possible damage. From the zone of possible damage, and based on experience from other membrane LNG ships, the likely contribution of any possible localised damage to the overall tank vacuum decay rate (VDR) can be estimated.

Hearing tests and global AE may detect and locate indications in way of the tank walls. Using localised AE readings TID can give the precise location of these indications therefore reducing the amount of excavation required to expose the defect, plus quantify the magnitude of the defect, which assists in the overall assessment of cargo tank integrity.
Comparison of AE approaches

The Modal acoustic emission (MAE) approach is targeted towards lower frequencies, and a broader band, than those used in more conventional AE, in particular the global and local AE cited above. A simplistic comparison is:

- Modal AE for CPRVs – “broadband” frequency range, focussing on 5 to 500 kHz;
- Global AE for CCS – “broadband”, focussing in range (approximately) 10 to 100 kHz;
- Local AE for CCS – “narrowband”, focussing on 20 to 40 kHz (centred around ~30 kHz).

A consequence of the frequency ranges chosen is the necessary sensor spacing to ensure reliable detection (Reference 6). A simplistic comparison is:

- Modal AE for CPRVs – sensor spacing variable, depending on what frequencies are most significant within the relatively wide frequency band, typically between 0.1 and 10m;
- Global AE for CCS – sensor spacing typically 2 to 3 m;
- Local AE for CCS – sensor spacing variable typically 0.3 to 0.5 m but dependent on magnitude of signal and resolution desired.

Conclusions

This paper has considered two different types of composite containment system, and two different types of acoustic emission (AE) monitoring approach. Detailed technical data have not been included, due to client confidentiality constraints.

For the CPRVs, Modal acoustic emission (MAE) testing has been deployed at both the manufacturing and in-service stages. During manufacturing the primary focus has been on the integrity of the composite overwrap. In-service, the primary focus has been on the integrity of the steel cylinder (welded joints). For the membrane LNG ship CCS, a combination of LDPT, SBTT, hearing tests, global AE and localised AE have been used in effective combination to minimise the period that the ship may be out of service during the special survey required by classification and IMO regulations.

It is concluded that AE monitoring has taken an important role in the damage assessment of the two example composite cargo containment systems. It is inferred that AE monitoring will be able to take an important role in the damage assessment of other types of composite containment system.

References (more comprehensive set of references included within [1] and [6] below)

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