Technical reports

Acoustic emission, an innovative diagnosis tool for therapeutic hyperbaric chambers: or how to requalify safely using pneumatic pressure test

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Abstract

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Therapeutic hyperbaric chambers require continuous monitoring and maintenance, including periodic requalification. The primary aim is to verify the suitability for continued safe service. Maintenance is regulated in Europe, and in France requalification is mandatory where a hyperbaric chamber operates above pressures equal to or greater than 4 bar gauge. French requalification requires a hydraulic (hydrostatic) pressure test to determine the absence of deformation and leaks during the test. However, in such cases, it is often necessary to move the chamber if the combined mass of the chamber and water may exceed the allowable floor loading strength. In 2009, an innovative alternative to a hydraulic pressure testing was authorised in France. It consists of carrying out a pneumatic pressure test simultaneously with a non-destructive monitoring technique called 'acoustic emission'. This can be compared to a microseismology technique, where sensors are applied to the pressure retaining boundary of the hyperbaric chamber, and signals emitted by the vessel under load are captured. These signals are analysed, prioritised, and classified, to determine the physical position of any sources (artifacts) through triangulation calculations. This technique makes it possible to assess the behaviour of the vessel very accurately in real time and, *a posteriori*, to assess its fitness for continued service. This technique reduces the unavailability time of the chamber to two days, compared to potentially several weeks when a hydraulic test is performed. Over and above financial considerations and availability of facilities, this technique provides a baseline of the integrity of pressure vessels and allows monitoring over time of any potential deterioration.

Introduction

All pressure vessels, and especially those intended for human occupancy, require continuous inspection and periodic maintenance. Depending on local regulations, inspection and testing of the integrity of the pressure boundary may be legally mandated. In some European countries, and particularly in France, this periodic requalification is mandatory every 10 years for pressure vessels operating at a pressure equal to or greater than 4 Bar gauge (Barg).[1–4] In France, this requalification is carried out by means of a hydraulic (hydrostatic) test, usually conducted using water. The test may require, for reasons of insufficient allowable floor loads, moving the hyperbaric chamber to a more secure location. This allows for it to be filled with water and then pressurised to a pre-determined test pressure value (referred to as a hydrostatic test). The chamber is then checked for the absence of deformation and leaks. This entails a complex operation as internal equipment is usually required to be dismantled and removed. External equipment needs to be isolated from exposure to both water and elevated pressure. This is expensive, results in the hyperbaric chamber being out of service for a significant period of time, and can even cause damage (hydrostatic test pressure is more than the chamber's design pressure). Many centres do not perform this ten-year requalification, deeming it too costly or too restrictive. The hyperbaric chamber may then be downgraded and lose its ability to be compressed to equal to or greater than 4 Barg. Note that no therapeutic hyperbaric chamber limited to 4 Barg can perform HBOT at 4 Barg. In fact, the chambers are equipped with safety valves which must open at the authorised pressure limit. This limit cannot therefore be the pressure prescribed for treatment.

Given our clinical activity, it was deemed essential to maintain the possibility of higher pressure exposures for several reasons. The first is to be able to test our equipment.[5] Any non-CE approved hyperbaric equipment must be pressurised to our maximum, normal working pressure of 3 Barg for certain indications (air embolism, decompression accidents)[6] and may even require testing beyond this working depth. Our validation procedures require that we test applicable patient care equipment to a higher pressure than the intended maximum working pressure. Therefore, without the capability of being pressurised to at least 4 Barg, beds, glucometers or other equipment essential to the proper care of patients would not be authorised for use in our hyperbaric chamber. Testing of equipment above 4 Barg is financially very challenging.[7] We also offer an educational service to diving clubs through a visit to our center, where we provide an awareness of narcosis through psychometric tests during a dry dive to 4 or 5 Barg. Finally, diploma training and assessing aptitude for work in a hyperbaric environment requires training where students undertake dry dives at 5 Barg in order to obtain certification as a medical hyperbaric worker.[8] There are no longer any strong indications to use therapeutic exposures at more than 3 Barg.

Hyperbaric chambers are therapeutic devices often installed in areas with reduced visual access. Most of them are in high demand. Indeed, each treats numerous patients, some of whom have urgent and vital indications such as gas embolism,[9] decompression sickness,[10] carbon monoxide poisoning[11] or gas gangrene.[12] Closing a hyperbaric chamber, even temporarily, can compromise a healthcare system.[13] Requalification, although necessary, must close the hyperbaric chamber for as short a time as possible. Finding an alternative to the hydraulic test was therefore desirable. However, a pneumatic test on its own is not allowed in France. An acoustic emission test carried out during a pneumatic pressure test was the only solution, allowed under French legislation since 2009.[3] This innovative technique goes beyond the simple possibility of replacing the hydraulic test, as it allows a more precise and reliable diagnosis of the structural integrity of the vessel. Our hyperbaric centre considered this alternative, evaluated its feasibility performed the testing, and is publishing its conclusions so that other centers may potentially benefit from it.

Methods

Acoustic emission testing is performed by installing passive piezoelectric sensors (resonant frequencies between 100 and 500 kHz) on a pressure vessel. Each position and distance to neighboring sensors is defined by:

- regulatory rules, codes and guides such as the ASME Boiler and Pressure Vessels Code,[14] European Standards (EN14584)[15] and the French technical guide for good practices for acoustic emission control of pressure equipment.[3]
- a desired location accuracy objective (basic location by area or precise planar location), and
- the experience of the qualified person in charge of the tests, who will be able to adapt the mesh (position of the sensors on the structure) to the specificities of the vessel, such as geometric discontinuities.[16]

Once the sensors are in place, a data acquisition system records the acoustic signals generated by the vessel when pressurised. This system, coupled with a computer, provides data in real time.

REQUIREMENTS RELATED TO TEST PRESSURE

The pressurisation cycle is made up of phases of pressure rise, in increments, and successive depressurisations. In order to respect code- or standards-defined constraints on one hand and technical constraints on the other, the maximum test pressure corresponds to the greater of the following two values:

- the value linked to the acoustic emission technique, which requires applying pressure at least 10% in excess of the actual maximum pressure applied in service in the preceding six months ('110% actual maximum pressure'); or
- the applicable regulation rules, which may require a test pressure of between 90% and 110% of the maximum allowable pressure.

CONFIGURATION OF INSTRUMENTATION USED

The configuration recommended for carrying out such an examination control is a mesh of sensors sufficiently dense to allow planar localisation. Thus, any source of acoustic emission at least as energetic as the reference source (called Hsu-Nielsen source) can be located by triangulation, which is based on the same principles for locating the epicenters of earthquakes in the field of seismology.

INSTALLATION AND VERIFICATION OF SENSITIVITIES OF THE SENSORS

The sensors used for this type of application are 150 kHz piezoelectric resonant (ultrasonic) sensors. This frequency in the ultrasonic range is most suitable for detecting damage phenomena in metallic materials (such as cracking, microcracking, etc.). In addition, being far from the audible frequency domain, acoustic emission can be used in a wide range of industrial environments.

Once the sensors are installed and connected to the data acquisition system via a preamplifier, the sensitivity level is checked using a reference source. This phase is essential to ensure the quality of the coupling between the sensor and the pressure vessel, and therefore ensuring good transmission of the ultrasonic waves. These installation, verification and thereafter dismantling phases can be carried out during normal operation of the chamber.

ANALYSIS AND INTERPRETATION OF DATA

Acoustic emission is an extremely simple technique in principle, but demanding in terms of analysis. Often considered as a special, even exotic technique in the field of non-destructive testing, due to difficulties in understanding data processing, it needs to comply with the relevant codes and standards for all phases of application, including rigorous analysis of signals.[3,14,15,17–19]

The analysis of a test takes place in two stages:

1. Analysis in real time, i.e., when pressure is applied to the vessel. This analysis integrates shutdown criteria, making it possible to secure the test under pneumatic pressure, and anticipates potential premature failure of the equipment.
2. A delayed-time analysis which leads to precise conclusions on the strongest emitting areas of the vessel. This emissivity is quantified by classification into categories (from category 1: notable/non-critical acoustic activity to category 3: intense acoustic activity, requiring additional investigation).

At the end of a test, the qualified person in charge of acoustic emission examination can immediately provide initial indications on the state of health of the vessel.

Whether in real or delayed time, several types of analysis, from the simplest to the most complex, make it possible to assess the integrity of the vessel.

Analysis of the background noise level of each sensor

This is carried out by measurement of the effective voltage of the signal (root mean square voltage value). This makes it possible to detect continuous phenomena, such as a leak, with great sensitivity.

Zonal analysis

Zonal analysis focuses on impulse signals (called bursts) whose origin can be the progression of microcracks or fracture of fragile corrosion layers (all discrete phenomena by nature). It consists of allocating a series of bursts resulting from the same physical phenomenon to the first sensor reached. We can therefore simply localise the source, although without significant accuracy. This analysis has the advantage of being simple, defined in the codes and standards, and results in the classification (into three categories) of each area covered by a sensor using numerous analysis criteria.

Planar localisation-based analysis

This is the most complex processing involving calculating the coordinates of the epicenter of the acoustic emission sources by carrying out triangulation calculations based on the arrival times of the signals. The accuracy of the result depends on several factors:

- the quality of the mesh of sensors used (number, distance between sensors, placement accuracy, etc.);
- the wave propagation speed; and
- the precision of determining the signals arrival times (which requires precisions of less than a microsecond).

This analysis results in a map of the acoustic activity of the monitored vessel. The most emissive regions of the vessel are automatically identified using the concept of ‘clusters’ (spatial grouping of several events). Used in the field of acoustic emission for nearly 30 years, whether in real time (during the test) or in delayed time, this methodology makes it possible to identify the most active regions very quickly and precisely. However, it is important to emphasise that the reliable use of planar localisation requires:

- a denser network of sensors than for simple zonal localisation;
- optimal listening conditions requiring the total cessation of sessions in the tested hyperbaric chambers; and
- mastery of all calculation parameters by the engineers in charge of these tests.

Today, the most advanced codes and standards in the field of acoustic emission, applied to the evaluation of pressure equipment, strongly recommend the systematic application of planar localisation. Consequently, this applies to the instrumentation conditions to achieve this, by proposing a methodology which makes it possible to quantify the expected performance of a sensor network (ASME, BPVC 2023, Section V, Article 12 – Mandatory Annex n°3).[14]

REQUIREMENTS RELATED TO PRESSURE

Our hyperbaric chamber is made up of two compartments (‘Poseidon’ and ‘Scylla’) andand can reach a pressure of 6 Barg. Therefore, the maximum test pressure was set at 6.6 Barg. Figure 1 illustrates the pressurisation cycle defined in the test procedure and which must be applied in the case of the Poseidon hyperbaric chamber.

INSTRUMENTATION USED

Hyperbaric chambers often have complex shapes and are made up of several elements. The rules of the acoustic emission technique had to be adapted to these specificities. We have thus taken advantage of the localisation capabilities of this technique. In doing so, it becomes possible to detect and locate any defects potentially harmful to the vessel with a precision of a few centimeters for a hyperbaric chamber having a total volume of more than 30 m^3.

A precise mesh of sensors adapted to the geometries of the Poseidon chamber and the Scylla airlock was defined based on acoustic wave attenuation measurements (Figure 2). The mesh of sensors also takes into account the geometric

Figure 1

Theoretical pressurisation cycle (the Poseidon hyperbaric chamber and its airlock); Barg – pressure in Bar (gauge)

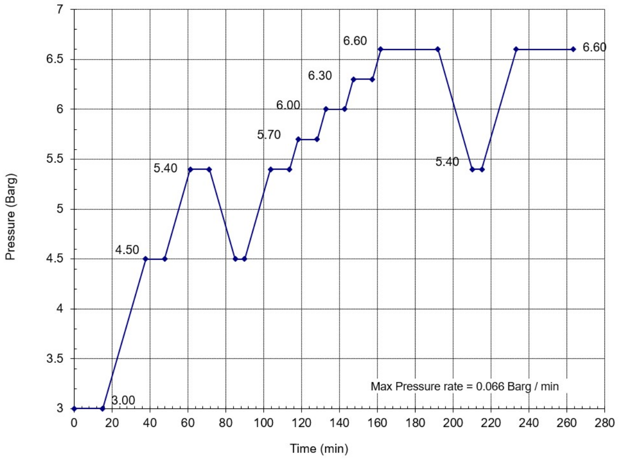


Figure 2

Typical attenuation curve taken into account (hyperbaric chamber - direction perpendicular to the reinforcements); dB_{ae} – acoustic emission signal amplitude unit

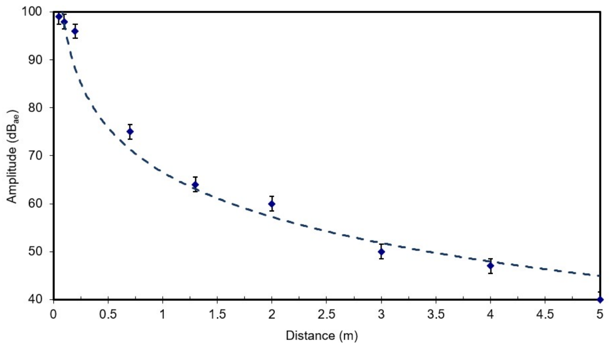


Figure 3

General view of the sensors mesh for Poseidon chamber (the position of the sensors is symbolised by yellow circles)

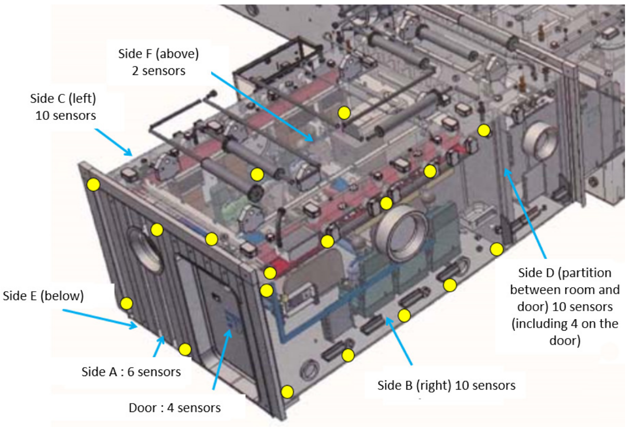
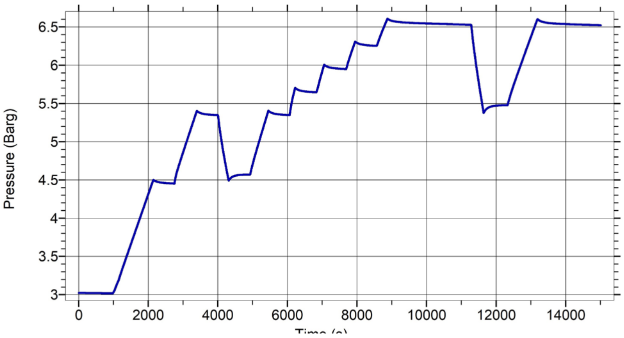


Figure 4

Actual pressurisation cycle (Scylla airlock); Barg – pressure in Bar (gauge)



particularities of these vessels such as the square chamber shell, the presence of numerous reinforcements (which cause propagation asymmetry), discontinuities such as doors (which disrupt the propagation of waves), and areas sometimes inaccessible. Thus, beyond compliance with codes, standards and application guides, it is appropriate to have a sufficient level of expertise to define a network of sensors (43 sensors were installed for Poseidon and 28 for Scylla) to ensure complete coverage of each vessel (Figure 3).

OPERATING PROCEDURE AND PREPARATION AHEAD OF THE REQUALIFICATION OPERATION

During the months preceding the deadline we had to collect technical acoustic emission data, in order to define and configure the means of pneumatic pressurisation, and prepare the necessary documents so that the authorised body could give us a favorable notice on the file.

PRESSURE TESTING AND ITS REAL–TIME MONITORING

Compliance with the pressurisation cycle defined in the test procedure is essential. Also, the engineers in charge of the hyperbaric chambers at the Lille University Hospital configured the means of pressurisation to allow, on the one hand, the recommended cycle to be respected (Figure 4), but on the other hand, to make pressurisation of the vessel as quiet as possible (so as not to disturb the sensors).

In this case, it made it possible to carry out these tests highly accurately and effectively, and thus respect the planning constraints, namely test completion before noon, oxygen therapy sessions resumed as planned at the beginning of the afternoon.

Results

ANALYSIS AND INTERPRETATION OF DATA

Analysis of the background noise level

In the case of the pressure test of the Scylla airlock, this analysis made it possible to highlight a minor leak which was not detectable from a pressure measurement but nevertheless present. Figure 5 shows the root mean square voltage values for each sensor. The most affected sensor in this case being sensor c2 (channel 2), which revealed a minor leak in the area of the door between Poseidon and Scylla.

Zonal analysis

Figure 6 illustrates a summary of the zonal analysis of Scylla. In particular, we were able to observe that the area covered by sensor c3 was the most emissive (events vs channel graphs, at the right).

Planar localisation-based analysis

Figure 7 illustrates the acoustic activity map for part of the Scylla airlock.

SYNTHESIS FROM THE TESTS ON THE POSEIDON CHAMBER AND THE SCYLLA AIRLOCK

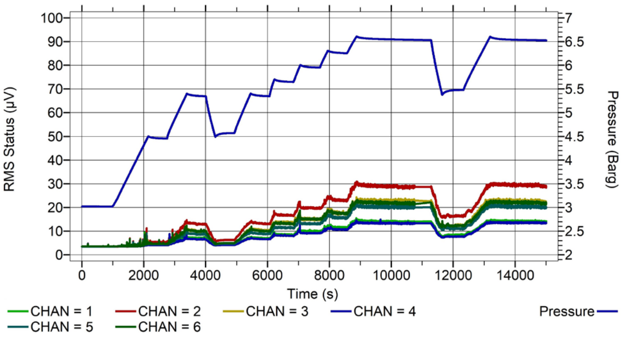
The acoustic emission controls of the two compartments were carried out successfully and resulted in requalification of the complete chamber. Only two half-days of unavailability were necessary to carry out these operations, with many of the preparatory phases being able to be carried out while normal treatments were underway. The acoustic broadcast highlighted:

- For Poseidon, four regions classified in category two, corresponding to particular areas (weld portions, viewport flange welding connection portion).
- For Scylla, a region corresponding to part of the Scylla-Poseidon manway junction.
- Additional examinations were carried out on these areas (magnetic particle and ultrasonic inspections) which determined that the vessels were still compliant and safe for continued service.

Discussion

Figure 5

Analysis of the Scylla airlock test showing root mean square (RMS) voltage values recorded for channels c1 to c6; CHAN – sensor channel



During the acoustic emission test, we detected small anomalies such as the detection of a leak in the area of the door between Poseidon and Scylla. The high sensitivity of the acoustic emission technique to turbulent flow enabled the detection of a small leak that would otherwise be imperceptible. Thanks to a dense network of sensors, it was possible to localise this leak. Moreover, as the data are continuously recorded during the test, acoustic emission can characterise the level of pressure from which the leak has been detected. A simple pressure test without acoustic emission monitoring would have not highlighted such leak, as the pressure loss is not easily measurable, and would not have been able to give any information on its localisation.

Acoustic emission testing revealed areas where activity was classified as Category 2, thus detecting regions of potential anomalies. Follow-up inspections using appropriate non-destructive evaluation techniques concluded that these indications were non-significant. Such anomalies would not be detected using a simple hydrostatic test. This illustrates the acoustic emission technique's advantages in being able to detect latent defects, providing precise location, and then allowing focused (or precise) additional investigative work to be done.

The overall finding is in no way negative, resulting in compliant requalification of the chambers. From a regulatory point of view, even if acoustic emission is very sensitive, it allows the requalification of a hyperbaric chamber without imposing any additional constraints compared to a traditional requalification.

Although the active areas have been considered as non-significant during this pressure test, information on their localisation and characteristics (including pressure threshold) will serve as a baseline for comparison at the next pressure tests (or next requalification). Since the acoustic emission technique gives an image of the behaviour of a structure under load, it is able to reveal the appearance of anomalies during the life of the structure.

Hyperbaric chambers are considered 'safety-critical' installations because they can, in the event of an incident, cause major, even catastrophic damage. Given that these facilities accommodate patients and caregivers, it is important to obtain accurate assessment of their fitness for service. Regulations may differ from one country to another but all require vessel integrity to be checked periodically. In Europe, when rated to operate at pressures greater than 3 Barg, this type of equipment is subject to periodic visual inspections (every 48 months) and requalification every

Figure 6

Zonal location analysis of the Scylla airlock test; Barg – pressure in Bar (gauge)

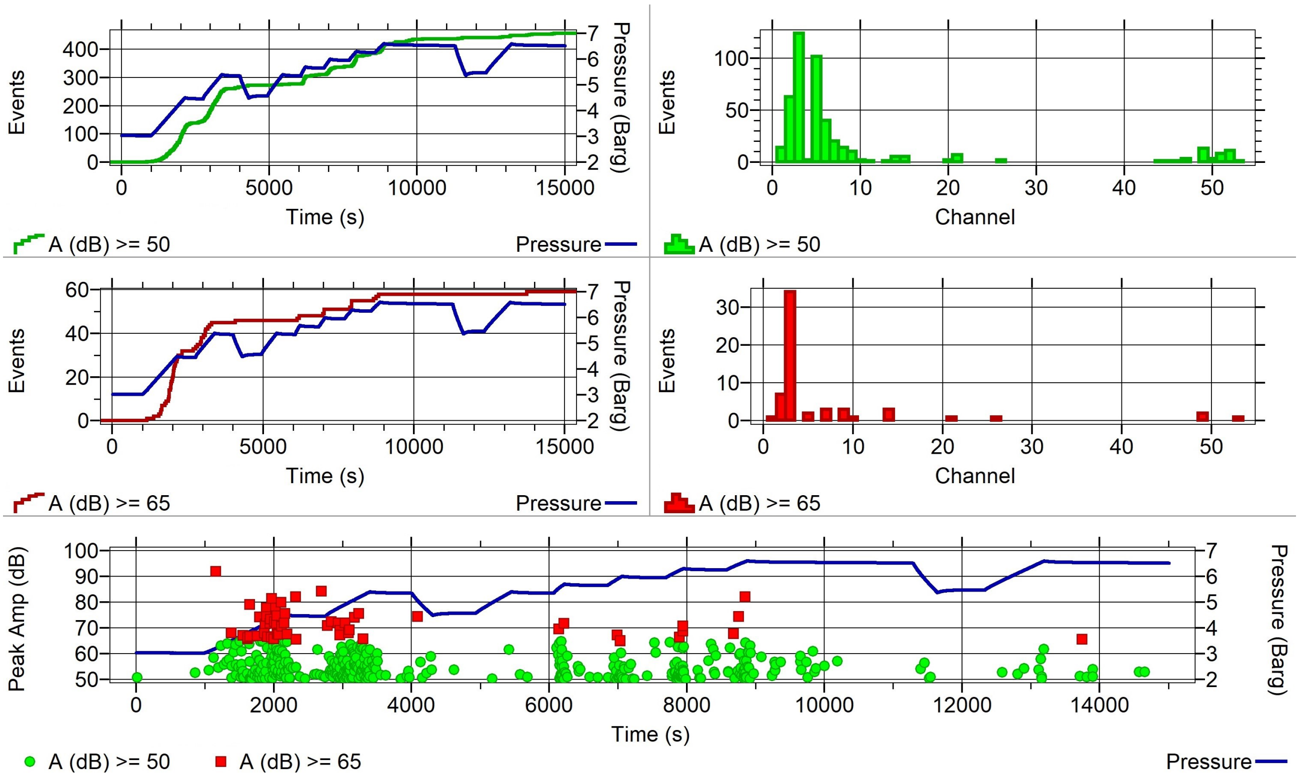
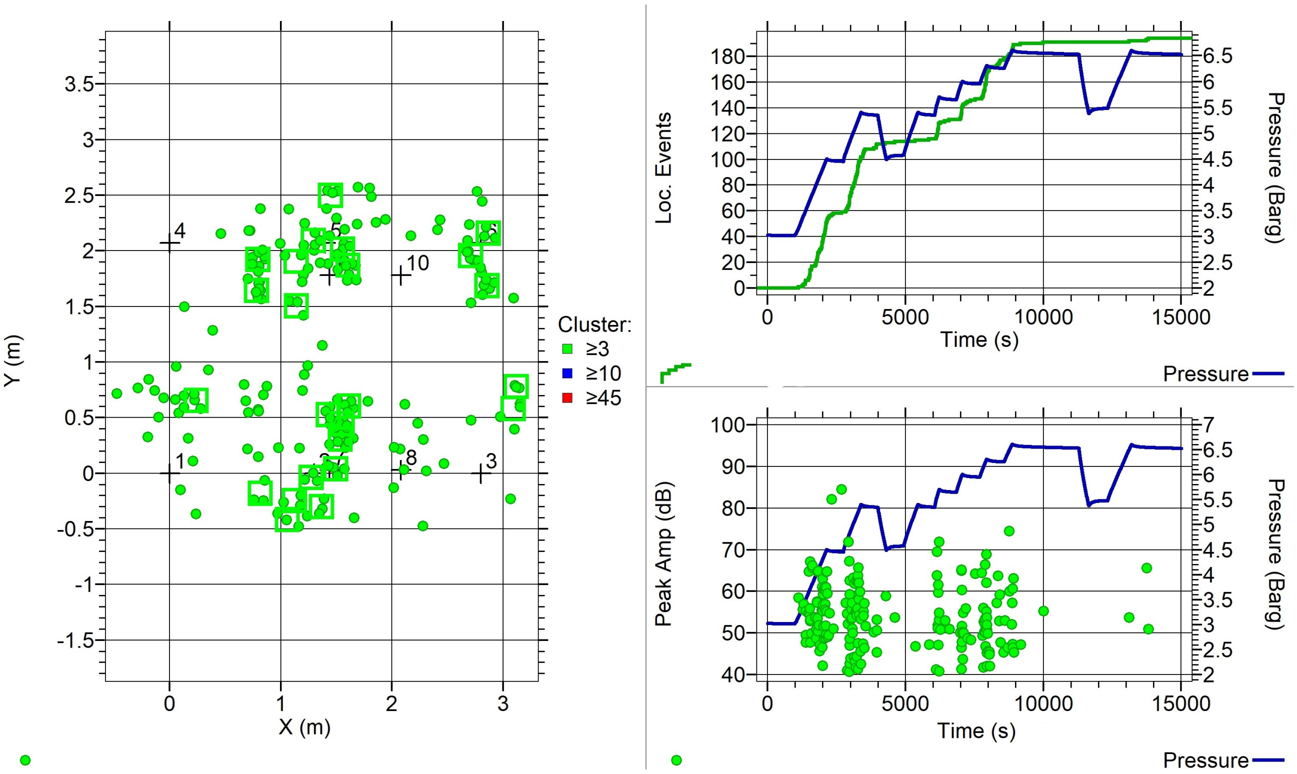


Figure 7

Planar location analysis of the Scylla airlock test; Barg – pressure in Bar (gauge) X & Y – coordinates of the located events



10 years. Traditionally, this requalification is based on a hydraulic test to ≥ 1.2 x maximum allowed pressure, requiring the following operations:

1. Complete dismantling of the chamber;
2. Inspection of the chamber by an authorised body;
3. Hydraulic testing which may involve moving the chamber to support the weight of the water;
4. Drying of the chamber then repainting;
5. Reassembly of all the elements of the chamber; and
6. Carrying out pressure (leak) tests before re-commissioning.

Beyond the fact that many of these operations can be tedious and time-consuming, involving substantial downtime (around three weeks), the hydraulic test does not allow a detailed diagnosis of the state of health of the vessel. Its diagnosis is binary; the equipment either resists or does not resist the pressure, it either leaks or it does not.

Acoustic emission is, today, the most suitable technique for evaluating the serviceability of vessels subjected to stress for several reasons:

1. It is by nature a monitoring technique; and
2. It is similar in many respects to seismology, it makes it possible to detect developments of potentially critical structural defects, and simultaneously, the appearance of even minor leaks.

Since the 1970s, this technique has been used to assess the fitness for service of pressure equipment, whether metallic or composite. The first code appeared in the 1980s in the United States,[14] and later in France and Europe. Today, this technique is recognised statutorily, and the necessary requalification can be based on the result of an acoustic emission test carried out during a pneumatic pressure test.

Several hyperbaric chambers have been able to benefit from the advantages of this technique such as Nice University Hospital and Angers University Hospital. To our knowledge, these chambers (Nice, Angers, Lille) are the only ones that have been requalified in this way. This innovative method has many advantages including:

1. Dismantling operations are no longer necessary;
2. The constraints linked to the hydraulic test are removed;
3. The operations of drying and reassembling accessories are also eliminated;
4. The diagnosis is more precise (mapping the emissivity of the vessel); and
5. Downtime is reduced drastically.

The acoustic emission method makes it possible to obtain precise information on the dynamic behavior of even complex vessels. It is a conservative method in that the results are sufficiently accurate to detect damage phenomena well before they pose a risk of failure. It allows engineers to have a baseline, ongoing history, and thus detect changes over time (acoustic emission is increasingly used, particularly in the field of condition monitoring). In addition to saving time, it saves floor load calculation work which needs to be carried out by civil engineering teams.

Acoustic emission was also successfully performed on the hyperbaric facility's eight air buffer tanks, each rated at 4,000 liters at 12 Barg, again reducing costs primarily as a result of reduced downtime.

Conclusions

The acoustic emission technique can be the most effective and least expensive tool in obtaining a very precise assessment of the state of health of a vessel under pressure while avoiding long unavailability of the hyperbaric installation. This provides a higher level of confidence in the integrity of all parts of the vessels, together with a baseline for comparison of future tests. We hope that the results of this study will allow other hyperbaric centres to consider this useful and effective alternative to hydraulic tests.

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