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Gas cylinders — Cylinders and tubes of composite construction — Modal acoustic emission (MAE) testing for periodic inspection and testing

Bouteilles à gaz — Bouteilles et tubes composites — Essai par émission acoustique modale (EAM) pour les besoins du contrôle et des essais périodiques

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Contents

Page

Foreword ..... **v**

Introduction ..... **vi**

1 Scope **1**

2 Normative references **1**

3 Terms, definitions and symbols **1**
3.1 Terms and definitions 1
3.2 Symbols 5

4 Modal acoustic emission (MAE) general operational principles **6**

5 Personnel qualification **6**

6 Test validity **6**

7 Calibration **6**
7.1 Absolute sensor calibration 6
7.2 Rolling ball impact calibration 7
7.2.1 General 7
7.2.2 Direct calibration 8
7.2.3 Linearity calibration 8
7.3 MAE wave recording system calibration 8

8 MAE testing equipment **9**

9 MAE testing **9**
9.1 General 9
9.2 MAE testing procedure 9
9.2.1 General 9
9.2.2 Sensor coupling 10
9.2.3 Sensor positioning 10
9.2.4 Attenuation measurement 11
9.2.5 System settings 11
9.2.6 System sampling rate 11
9.2.7 Sensor coupling checks 11
9.2.8 Pressurisation test methods 11
9.2.9 Repeating MAE testing 12

10 Interpretation **13**
10.1 General 13
10.2 Noise filtering 13
10.2.1 General 13
10.2.2 Electromagnetic interference (EMI) 14
10.2.3 Mechanical rubbing 14
10.2.4 Flow noise 14
10.2.5 Leakage 14
10.2.6 Clean front end 14
10.3 Data analysis 14

11 Evaluation and rejection criteria **14**
11.1 Evaluation 14
11.2 Analysis procedure 15
11.2.1 General 15
11.2.2 Rejection due to partial fibre bundle rupture criteria 15
11.2.3 Rejection due to single event energy 15
11.2.4 Rejection due to background energy (BE) and background energy oscillation (BEO) 15

12 Test report **16**

13 Rejection and rendering cylinders unserviceable 16
Annex A (normative) **MAE testing equipment specification** 17
Annex B (informative) **Overview of modal acoustic emission (MAE) test method** 19
Bibliography 24

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 58, *Gas cylinders*, Subcommittee SC 4, *Operational requirements for gas cylinders*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In recent years, new non-destructive examination (NDE) techniques have been successfully introduced as an alternative to the conventional retesting procedures of gas cylinders, tubes and other cylinders.

One of the alternative NDE methods for certain applications is acoustic emission testing (AT), which in several countries has proved to be an acceptable testing method applied during periodic inspection. This AT method is described in ISO 16148, which authorizes pressurization pneumatically to a value equal to 110 % of the cylinder's working pressure and hydraulic pressurization to a value equal to the cylinder's test pressure. Since ISO 16148 was developed for periodic inspection and testing of monolithic materials (seamless steel and aluminium-alloy cylinders), the test method was not appropriate for composite cylinders. The modal acoustic emission (MAE) test method described in this document was developed to address this shortcoming.

The MAE test method described in this document applies during periodic inspection and testing, and it uses either hydraulic (liquid) pressurization or pneumatic (gas) pressurization to a level equal to the design test pressure of the cylinder. It detects structural damage that can result in a compromised burst pressure strength in a composite cylinder. The MAE waveforms can be used to identify damage such as fibre breakage and delamination. An MAE waveform is distinguished by the wave (mode) shapes, velocities, waveform energy and frequency spectrums. This MAE test method is not intended for newly manufactured composite cylinders.

The application of MAE testing on composite overwrapped gas cylinders with metallic and polymer liners was applied to a sample of composite cylinders [180 self-contained breathing apparatus (SCBA) cylinders selected from 50 000] that were near the end of their 15-year service life. The MAE testing was performed during physical testing, which was similar to design qualification testing for this type of composite cylinder. The physical testing included pressure cycling, burst testing, flaw tolerance testing and ISO 11119-2 drop testing. The MAE testing consistently detected and differentiated each cylinder that had a compromised burst pressure strength, which had been defined for this project to be a pressure less than the original design burst pressure of the cylinder, by the presence of background energy oscillation (BEO) at or near the test pressure.

Gas cylinders — Cylinders and tubes of composite construction — Modal acoustic emission (MAE) testing for periodic inspection and testing

CAUTION — Some of the tests specified in this document involve the use of processes (e.g. pneumatic pressurization) which could lead to a hazardous situation.

1 Scope

This document describes the use of modal acoustic emission (MAE) testing during periodic inspection and testing of hoop wrapped and fully wrapped composite transportable gas cylinders and tubes, with aluminium-alloy, steel or non-metallic liners or of linerless construction, intended for compressed and liquefied gases under pressure.

This document addresses the periodic inspection and testing of composite cylinders constructed to ISO 11119-1, ISO 11119-2, ISO 11119-3, ISO 11515 and ISO/TS 17519 and can be applied to other composite cylinders designed to comparable standards when authorized by the competent authority.

Unless noted by exception, the use of "cylinder" in this document refers to both cylinders and tubes.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

ISO 11623, *Gas cylinders — Composite construction — Periodic inspection and testing*

ASTM E1106-12, *Standard Test Method for Primary Calibration of Acoustic Emission Sensor*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
modal acoustic emission
MAE
branch of acoustic emission (AT) focused on the detection, capture and analysis of the sound waves generated by acoustic events due to *fibre tow* (3.1.19) breakage, cracking, crazing, rubbing, delamination or fracture of structural components

Note 1 to entry: The sound waves can be produced either by defects [e.g. *fibre tow* (3.1.19) breakage, crack growth, delamination] or by surface rubbing. The wave frequencies typically extend from the sonic to the lower ultrasonic range. MAE is distinguished from AT by its focus on capturing waveforms with broader bandwidth sensors and analysing the waveforms according to wave propagation physics in an attempt to determine the type of source, as is done in seismology, whereas AT has been generally concerned with counts, amplitudes and other signal features based on different theories of analysis than MAE.

3.1.2
broadband piezoelectric sensor
sensor having a response that is flat-with-frequency (±6 dB) when calibrated in an absolute sense over the frequency range of interest

Note 1 to entry: Due to a lack of signal distortion or "coloration", broadband piezoelectric sensors enable the observation of the extensional and flexural plate waves which facilitates the direct comparison to physical models for proper damage mechanism identification.

3.1.3
preamplifier
amplifier that converts a lower level voltage signal to a higher level voltage signal

Note 1 to entry: A preamplifier can also have a 0 dB gain where it would function purely as a buffer or unity gain amplifier.

3.1.4
high-pass filter
electronic filter applied to the wave signals to reduce mechanical noise

3.1.5
low-pass filter
electronic filter applied to the wave signals to prevent *aliasing* (3.1.13)

3.1.6
analogue-to-digital converter
A/D converter
electronic device that changes an analogue electrical signal into a digital representation

3.1.7
input impedance
value of the impedance, denoted as Z, at the input to the voltage *preamplifier* (3.1.3) to which the transducer is directly connected

3.1.8
Nyquist frequency
bandwidth of the sampled signal, equal to half the sampling rate

3.1.9
primary AE
acoustic emissions caused by damage mechanisms (e.g. fracture, crack propagation, defect growth) originating from the material under test

3.1.10
secondary AE
acoustic emissions caused by sources other than damage mechanisms originating from the material under test (frictional rubbing against containment, EMI, flow noise, etc.)

Note 1 to entry: See Clause 10 for information regarding filtering out extraneous noise.

3.1.11
background energy
BE
minimum energy in a windowed portion of a given waveform

3.1.12
background energy oscillation
BEO
excursion of greater than *BEO multiplication factor* (M_2) (3.1.26) between neighbouring maxima and minima of an N point moving average calculated from all *background energy* (3.1.11) values

3.1.13
aliasing
effect resulting from under sampling that causes different signals to become indistinguishable (or aliases of one another) when sampled

3.1.14
clean front end
pre-trigger energy of less than 0,01 × 10^{-15} J when accounting for gain

3.1.15
working pressure
settled pressure of a compressed gas at a uniform reference temperature of 15 °C in a full gas cylinder

Note 1 to entry: In North America, service pressure is often used to indicate a similar condition, usually at 21,1 °C (70 °F).

Note 2 to entry: In East Asia, service pressure is often used to indicate a similar condition, usually at 35 °C.

[SOURCE: ISO 10286:2015, 736]

3.1.16
developed pressure
pressure developed by the gas contents in a cylinder at a uniform reference temperature of $Temp_{\mathrm{max}}$

Note 1 to entry: $Temp_{\mathrm{max}}$ is the expected maximum uniform temperature in normal service as specified in international or national cylinder filling regulations.

[SOURCE: ISO 10286:2015, 733, modified — “T_{max}” replaced with “$Temp_{max}$”]

3.1.17
composite overwrap
combination of *fibres* (3.1.18) and *matrix* (3.1.20)

3.1.18
fibre
load-carrying part of the *composite overwrap* (3.1.17)

EXAMPLE Glass, aramid or carbon.

3.1.19
fibre tow
group or bundle of *fibres* (3.1.18)

3.1.20
matrix
material used to bind and hold *fibres* (3.1.18) in place

3.1.21
extensional waves
collection of wave modes characterized by dominant in-plane deformation characteristics

Note 1 to entry: Extensional wave modes are analogous to symmetric (S) wave modes in isotropic plate-type structures.

3.1.22
flexural waves
collection of wave modes characterized by dominant out-of-plane deformation characteristics

Note 1 to entry: Flexural wave modes are analogous to antisymmetric (A) wave modes in isotropic plate-type structures.

3.1.23
fibre bundle rupture energy multiplication factor
$\boldsymbol{F_1}$
allowance factor for *fibre* (3.1.18) bundle rupture energy

Note 1 to entry: The value of F_1 is determined by analysis of the composite material and pressure vessel design.

3.1.24
total single event energy multiplication factor
$\boldsymbol{F_2}$
allowance factor for single event energy

3.1.25
BE multiplication factor
$\boldsymbol{M_1}$
multiplicative factor that corresponds to a rise in the *background energy* (3.1.11) level above the quiescent level

Note 1 to entry: The value of M_1 is a function of vessel type, *fibre* (3.1.18) construction, size and pressure rating of the composite cylinder and is determined through theory and/or testing.

Note 2 to entry: M_1 indicates that the damage accumulation has commenced in the composite pressure vessel under test.

Note 3 to entry: See 3.1.27.

3.1.26
BEO multiplication factor
$\boldsymbol{M_2}$
difference factor between neighbouring maxima and minima of an N point moving average calculated from all *background energy* (3.1.11) values

Note 1 to entry: The value of M_2 is a function of vessel type, *fibre* (3.1.18) construction, size and pressure rating of the composite cylinder and is determined through theory and/or testing.

Note 2 to entry: M_2 indicates that the composite pressure vessel under test is progressing towards failure.

3.1.27
quiescent background energy
$\boldsymbol{U_{QE}}$
energy determined in a windowed portion of a waveform during a period of inactivity

3.1.28
wave energy
$\boldsymbol{U_{\mathrm{WAVE}}}$

$$U_{\mathrm{WAVE}} = \frac{1}{z}\int_0^t V^2 dt$$

Note 1 to entry: For comparison to physical energy values (e.g. the theoretical energy released by a fibre fracture event), the total system gain is accounted for by dividing *V* by the gain factor before squaring, e.g. 40 dB gain is a gain factor of 100, 48 dB is a gain factor of 251,2, 60 dB is a gain factor of 1 000, etc.

3.2 Symbols

C_{E}	speed of the first arriving frequency in the E wave
C_{F}	speed of the last arriving frequency in the F wave
d	diameter of the fibre
E	Young's modulus of the fibre
ε	strain to failure of the fibre
g	acceleration due to gravity
h	vertical height of the centre of the rolling ball at the top of the inclined plane
I	ineffective fibre length for the fibre and matrix combination
L	distance between sensors, in m
m	mass
N	constant value relating to the type of fibre in the composite cylinder
T	period of the cycle
t_1	time, in µs, when the first part of the direct E wave will arrive (i.e. the arrival of the lowest observable frequency of interest in the E mode)
t_2	time, in µs, when the last part of the direct F wave will arrive (i.e. the arrival of the lowest observable frequency of interest in the F mode)
t	time
$Temp_{\mathrm{max}}$	expected maximum uniform temperature in normal service
$U_{\mathrm{FB}}^{\mathrm{AE}}$	energy produced by the occurrence of fibre breakage
$U_{\mathrm{FBB}}^{\mathrm{AE}}$	energy produced by the occurrence of fibre bundle breakage
$U^{\mathrm{AE}}{}_{\mathrm{RBI}}$	rolling ball impact acoustical wave energy
U_{FB}	theoretical fibre break energy
U_{mgh}	known mechanical energy
U_{RBI}	rolling ball impact energy

U_{WAVE} wave energy

V voltage

Z preamplifier input impedance

4 Modal acoustic emission (MAE) general operational principles

When a composite cylinder containing flaws is pressurized, stress waves can be generated by several different sources (fibre breakage, matrix cracking, delamination, etc.). These stress waves are defined as acoustic emissions (AE). The AE resulting from major flaws such as delamination or fibre bundle breakage starts at a pressure less than or equal to the test pressure of the cylinder. The internal pressure causes stress in the fibre overwrap which can result in AE waves that propagate throughout the structure. The AE waveform is captured, digitized and stored for analysis. MAE analysis essentially "fingerprints" each waveform by mode, energy and frequency content to determine the damage mechanism which occurred (delamination, matrix crack, fibre breakage, etc.). The connections between waveforms and fracture mechanisms have been determined through theoretical elastodynamic calculation and experiment and published in open literature.

The formulae for determining fibre break sources in composite cylinders are given in Annex A. Annex B provides examples for calculating fibre break energy and energy scaling, using representative values for F_1, F_2, M_1 and M_2, which are components of the formulae used to determine the reject criteria. After an MAE source is identified, this information is used to assess cylinder integrity. The values for rejection criteria are calculated as described in Clause 11.

NOTE The MAE test method described in this document is not intended for newly manufactured composite cylinders.

5 Personnel qualification

The MAE equipment shall be operated by, and its operation supervised by, qualified and experienced personnel only, certified in accordance with ISO 9712 or equivalent (e.g. ASNT SNT-TC-1A). The operator shall be certified to Level I and this individual shall be supervised by a Level II person. The testing organization shall retain a Level III (company employee or a third party) to oversee the organization's entire MAE programme.

6 Test validity

The type of construction of the cylinder (e.g. hoop or fully wrapped) and the type of fibre and resin (matrix) shall be known for input in the computer program (software) that analyses the MAE test.

To obtain an accurate MAE testing result, the cylinder should not have been pressurized to or above the MAE test pressure within the past 12 months prior to the requalification. However, if suspected external damage has occurred to the cylinder within 12 months of the previous requalification (mechanical impact, etc.), then an MAE test is recommended.

7 Calibration

7.1 Absolute sensor calibration

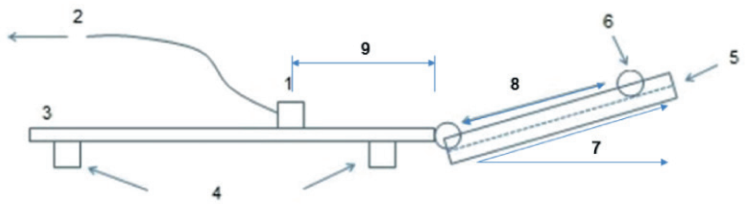
Sensors shall have a flat frequency response (±6 dB amplitude response over the frequency range specified, 50 kHz to 400 kHz) as determined by an absolute calibration. MAE sensors shall have a diameter no greater than 13 mm for the active part of the sensor face. The aperture effect shall be taken into account during MAE testing. Sensor sensitivity shall be at least 0,05 V/nm (with the removal of all amplification).

Absolute sensor calibration shall conform to the requirements specified in ASTM E1106-12.

7.2 Rolling ball impact calibration

7.2.1 General

The MAE system calibration or impact energy conversion shall be performed to detect and measure the wave energy of the test object (e.g. fibre breakage in a composite cylinder) by using the rolling ball impactor method. The rolling ball impactor is used to create an acoustical impulse in an aluminium-alloy calibration plate. Figure 1 illustrates the rolling ball impact setup.



Key

1	sensor	6	ball impactor
2	sensor output to MAE instrumentation	7	incline angle
3	aluminium-alloy calibration plate	8	rolling length
4	support blocks	9	propagation distance
5	inclined plane with groove		

Figure 1 — Example of a rolling ball impactor energy calibration setup

The setup shall include a 13-mm diameter ball made of a chrome steel alloy hardened to a minimum of HRC 63, ground and lapped to a minimum surface finish of 38 µm, within 2,5 µm of actual size and roundness within 0,6 µm.

The calibration plate shall be made of high strength 7000 series aluminium-alloy (e.g. 7075-T6) with a smooth surface, lateral dimensions of at least 1,20 m by 1,20 m and a thickness of 3 mm ± 10 % (e.g. maximum rolled flatness deviation of 3 mm/1 m). The calibration plate is supported by rigid blocks (e.g. steel or wood). The surface finish of the impact edge of the calibration plate shall be at least 13 µm RMS. The impact ball rolls down an inclined plane that has a 9,5 mm-wide by 2,5 mm-deep machined square groove that supports and guides it to the impact point. The length of the groove shall be a minimum of 400 mm, with a minimum surface finish of 26 µm RMS. The angle of the inclined plane shall be 6°.

The top surface of the inclined plane shall be positioned next to the edge of the calibration plate and stationed below the lower edge of the plate so that the ball impacts the calibration plate with equal parts of the ball projecting above and below the plane of the calibration plate (i.e. the tangent point of the ball impacts the centre plane of the plate). A mechanism (manual or automated) shall be used to release the impact ball down the inclined plane.

The system shall compute and record the measured wave energy.

7.2.2 Direct calibration

The sensor shall be placed on the calibration plate in a perpendicular orientation 300 mm ± 10 mm from the impact edge, in line with the impact location.

The sensor shall be mounted on the calibration plate using a couplant that prevents any air between the sensor and the surface of the calibration plate and tested separately via the rolling ball impact method. An MAE sensor may be damped in order to broaden the bandwidth. The vertical position of the ball's impact point shall be adjusted gradually in order to "peak up" the acoustical signal, such as is done in ultrasonic testing where the angle is varied slightly to peak up the response. The centre frequency of the first cycle of the extensional mode plate wave (E wave) shall be confirmed as 125 kHz ± 10 kHz. The energy value, in joules (J), of the received first cycle of the E mode wave is defined as $U^{\mathrm{AE}}{}_{\mathrm{RBI}}$, while the mechanical potential energy for the rolling ball is determined in the classical mechanics sense using Formula (1):

$$U_{\mathrm{mgh}} = m \times g \times h \tag{1}$$

$U^{\mathrm{AE}}{}_{\mathrm{RBI}}$ is the energy detected by the MAE system and is scaled by U_{mgh} in order to compare measured MAE fibre break waveforms to U_{FB} [see Formula (A.4)]. This shall be an "end-to-end" calibration, meaning that the energy is measured using the complete MAE instrumentation (sensor, cables, preamplifiers, amplifiers, filters and digitizer) that are to be used during the actual test.

7.2.3 Linearity calibration

The energy linearity of the complete MAE instrumentation shall be measured by using three different roll lengths (200 ± 10 mm, 300 ± 10 mm and 400 ± 10 mm) with a ±10 % tolerance. A representative sensor with a typical sensitivity curve may be used for the linearity check of the system. The centre frequency of the first cycle of the extensional mode plate wave (E wave) shall be confirmed as 125 kHz ± 10 kHz. The energy value, in joules (J), of the received first cycle of the E mode wave is defined as $U^{\mathrm{AE}}{}_{\mathrm{RBI}}$, while the mechanical potential energy for the rolling ball is determined in the classical mechanics sense using Formula (1).

7.3 MAE wave recording system calibration

The recording system (consisting of all amplifiers, filters and digitizers beyond the sensor) shall be calibrated by using a 20-cycle long tone burst with amplitude of 0,1 V at 100 kHz, 200 kHz, 300 kHz and 400 kHz. This calibration ensures that the sampling rate of the high speed analogue-to-digital (A/D) converter is functioning properly (e.g. not aliasing the waveform). For each frequency, the MAE calibration system shall be programmed to display an energy value using Formula (2):

$$U = \frac{\mathrm{V}^2 \times N \times T}{2Z} \tag{2}$$

where

V is equal to 0,1 volts;

N is equal to 20.

Formula (2) is valid for a system gain of 0 dB.

To ensure that a proper sampling rate has been set and that the energy measurement is functioning correctly, the measured values of energy shall be equal to the value calculated using Formula (2) with a tolerance of ±15 %.

8 MAE testing equipment

A typical MAE system includes:

— broadband piezoelectric sensors,

— preamplifiers,

— high- and low-pass filters,

— amplifiers,

— A/D converters,

— a computer program (software) for the collection of data,

— a computer and monitor for the display of data, and

— a computer program (software) for the analysis of data.

The MAE testing system shall include software capable of indicating the channel that detects the first arriving waveform. It shall also include sensors and recording equipment with a current calibration sticker (yearly) or a current certificate of calibration. Preamplifiers and amplifiers shall have a flat frequency response (±1 dB) over the sensor frequency specified. The MAE testing system shall include a high-pass filter of nominally 20 kHz. A high-pass filter as low as 5 kHz may be used if extraneous noise does not hamper the measurement. Also, a low-pass filter shall be applied to prevent digital aliasing that occurs if frequencies higher than the Nyquist frequency (half the sampling rate) are in the signal.

The MAE testing system shall also include the memory depth (wave window length) and sampling rate of the A/D converter and shall be set in accordance with the test requirement in Annex A. The software shall compute the rejection criteria energy values for the specific composite material after the operator inputs the required material properties and allowance factors, i.e. the fibre bundle rupture energy multiplication factor (F_1), the total single event energy multiplication factor (F_2), the BE multiplication factor (M_1) and the BEO multiplication factor (M_2). The software shall identify fibre rupture waveform signals and compare energies with acceptable energy values and compute both the quiescent BEs and BEs to compare against acceptable rise and oscillation energy values (see Annex A).

9 MAE testing

9.1 General

Prior to performing MAE testing, the external and internal surfaces of each cylinder shall be inspected in accordance with ISO 11623 or an equivalent standard accepted by the competent authority.

9.2 MAE testing procedure

9.2.1 General

After completion of the MAE system calibration and cylinder visual inspection, the MAE testing procedure in 9.2.2 to 9.2.9 shall be performed.

9.2.2 Sensor coupling

Each sensor shall be coupled to the cylinder in such a way that good ultrasonic coupling of the sensor to the part is assured, as described in 9.2.7. Good practice requires that care be taken to remove any air bubbles under the sensor that would interfere with wave transmission. Each sensor shall be connected to the testing equipment and a sensor performance check conducted prior to MAE testing to verify proper operation and good coupling to the cylinder (see 9.2.7).

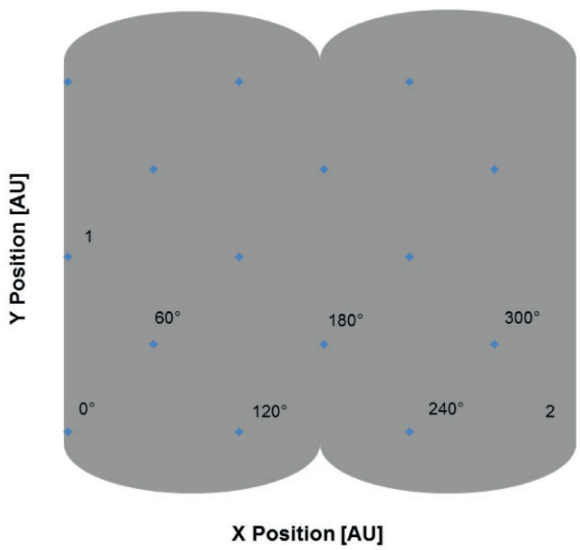
9.2.3 Sensor positioning

A minimum of two sensors shall be used for each cylinder, with one sensor installed at each end. Dependent upon cylinder size, additional sensors can be necessary. Sensors shall be positioned in rings, at equal distances around the circumference of the cylinder on its cylindrical portion adjacent to the tangent point of the dome such that the distance between sensors does not exceed 0,6 m in principal stress state directions. The sensors shall be located on the cylindrical section within 50 mm from the dome-to-shell transition area and in line to the axial direction of the cylinder.

If the sensor-to-sensor distance becomes greater than 0,6 m on large diameter cylinders for wave propagation in the dome portion of the cylinder, attenuation shall be measured (as described in 9.2.4) and appropriate sensors added to the dome portion. Adjacent rings of sensors shall be offset by half a cycle. However, if the attenuation of MAE is measured and found to be acceptable, the distance between sensors may be increased accordingly. Attenuation shall be measured by determining the maximum distance that the 400-kHz component of either the extensional or flexural wave (e.g., produced by a suitable source such as an ultrasonic pulser or a pencil lead break applied to a wedge with a relevant angle) can be observed with a signal-to-noise ratio of at least 1,4 using the sensitivity established in 9.2.5.

For example, if the first ring of sensors is placed at 0°, 120° and 240°, the second ring of sensors is placed at 60°, 180° and 300°. This pattern shall be continued along the length of the cylinder at evenly spaced intervals until the opposite end of the cylinder is reached.

See Figure 2 for an example of sensor positioning.



Key

1 broadband piezoelectric sensor

2 cylinder

Figure 2 — Example of sensor positioning for MAE testing

9.2.4 Attenuation measurement

The frequency and wave mode (extensional and flexural)-dependent attenuation behaviour of a cylinder of nominal design shall be measured and used for the normalization of measured energy values.

9.2.5 System settings

The threshold for each channel shall be a minimum sensitivity of 50 dB referred to 1 µV at the preamplifier input.

The system shall have minimum dynamic range of 65 dB.

9.2.6 System sampling rate

The sampling speed and memory depth (wave window length) are dictated by the test requirements. The wave window length shall include as a minimum the first part of the direct E wave and the last part of the direct F wave for a given event (pulse). One quarter of the window shall be reserved for pre-trigger memory (see Annex A).

The sampling rate, or sampling speed, shall be at least twice the maximum frequency present in the filtered waveform before A/D conversion so that aliasing does not occur.

9.2.7 Sensor coupling checks

Conduct sensor coupling checks prior to the test to verify proper operation and good coupling to the cylinder. For the coupling check, the superimposed E and F waveforms shall be observed by breaking and recording a 0,3 mm, 2H pencil lead at approximately 100 mm ± 10 mm from each sensor along the axial direction of the cylinder. The energy of the lead break waveforms shall be a minimum energy of $2{,}6E^{-15}$ J and the same within a factor of 4 for all sensors used in the test. If this energy comparison is not met by a sensor, the sensor shall be recoupled or replaced, and the sensor coupling shall be checked again to verify its energy is within the acceptable range. All lead breaks shall be recorded.

If an auto-sensor test is used in lieu of pencil lead breaks, all received waveform energies shall have the same values within a factor of 4. If so, repeat the lead breaks (or auto-sensor test) at a system gain that does not saturate the system. Prior to pressurization, reset the gain to the test gain.

All sensor coupling check data shall be recorded. The gain settings for the sensor coupling check shall be such that the signal does not saturate either the amplifiers or the A/D converter. If so, repeat the lead breaks at a system gain that does not saturate the system. Prior to pressurization, reset the gain to the test gain.

9.2.8 Pressurisation test methods

9.2.8.1 General

There are two pressurization methods that may be used during MAE testing. Both Method A (9.2.8.2) and Method B (9.2.8.3) are suitable for the periodic inspection and testing of composite cylinders. Each method has its own benefit. For example, Method A can provide additional information for cylinders that have a very high burst-to-test ratio; when using Method B, water does not need to be put into the cylinder.

The cylinder that is used for MAE testing shall be instrumented in accordance with 9.2.2 to 9.2.7 and then pressurized by either Method A or Method B. Based upon the test method selected, appropriate allowance factors shall be chosen (see B.3). The allowance factors used for each of the two methods are dependent upon the burst-to-test ratio developed in the laminate at the MAE test pressure.

WARNING — When performing the MAE test (especially pneumatically), safety precautions shall be taken to protect personnel carrying out the examination because of the considerable damage potential from the stored energy that can be released. Additionally, since MAE equipment might

not be explosion-proof, precautions shall be taken when the pneumatic pressurization gas is flammable.

Monitor and record the MAE event waveforms during the entire process. If detected MAE indications suggest that the cylinder could rupture, pressure should be released immediately.

Repeated pressurizations above the test pressure will compromise the MAE test result and can affect the structural integrity of the cylinder. The cylinder owner and manufacturer should be consulted for cylinder disposition.

During MAE testing, if a cylinder fails a test method, it is not permissible to use a different periodic inspection and testing method such as a proof pressure test to retest the cylinder.

9.2.8.2 Method A

MAE test pressure is equal to the cylinder's design test pressure. Each cylinder shall be subjected to a hydraulic pressurization from 0 bar to the cylinder's design test pressure, at which point a pressure-hold period will commence. The fill rate shall be less than the rate at which flow noise first appears. If at any time during fill, the fill rate is too high so that it causes flow noise, decrease the fill rate until the flow noise disappears.

If no MAE activity is recorded during any continuous 5-min period during the MAE test pressure hold, the pressure may be reduced to 0 bar and the test completed. If emissions are detected during the MAE test pressure hold, the cylinder shall be held at the MAE test pressure for a maximum of 15 min.

Conduct a post-test system sensitivity check (pencil lead breaks as described in 9.2.7) and record and save the data.

If the pre- and post-test sensitivities do not match, the MAE test is invalid.

9.2.8.3 Method B

If the previous maximum developed pressure experienced by the cylinder is not known, the MAE test pressure is equal to either 76 % of the cylinder's design test pressure or 5 % above the cylinder's developed pressure at 65 °C, whichever is greater. Each cylinder shall be subjected to a pneumatic pressurization from 0 bar to the MAE test pressure, at which point a pressure-hold period will commence. The fill rate shall be less than the rate at which flow noise first appears. If at any time during fill, the fill rate is too high so that it causes flow noise, decrease the fill rate until the flow noise disappears.

If no MAE activity is recorded during any continuous 5-min period during the MAE test pressure hold, the pressure may be reduced to 0 bar and the test completed. If emissions are detected during the MAE test pressure hold, the cylinder shall be held at the MAE test pressure for a maximum of 15 min.

Conduct a post-test system sensitivity check (pencil lead breaks as described in 9.2.7) and record and save the data.

If the pre- and post-test sensitivities do not match, the MAE test is invalid.

9.2.9 Repeating MAE testing

If any of the test equipment malfunctions at a pressure less than the cylinder's working pressure, the attempt is not considered a valid MAE test and the test may be repeated.

If any of the test equipment malfunctions at a pressure greater than or equal to the cylinder's working pressure, the test may be repeated up to three times provided the following conditions have been met.

— The test pressure for the repeated attempt shall be at least 5 % above the previous pressure at which the test equipment malfunction occurred.

— The maximum pressure for the repeated attempt shall not be greater than the cylinder's test pressure, unless the cylinder manufacturer approves pressurization of the cylinder to above the design test pressure.

If the data prior to the test equipment malfunction was saved, the MAE test may proceed to the MAE test pressure and all recorded data will be analysed. If the data prior to the test equipment malfunction was lost, the MAE test may be repeated starting at a pressure of 1 bar.

Figure 3 provides an illustration of when an MAE test may be repeated if equipment failure occurs and includes the necessary test pressure for the repeated MAE test.

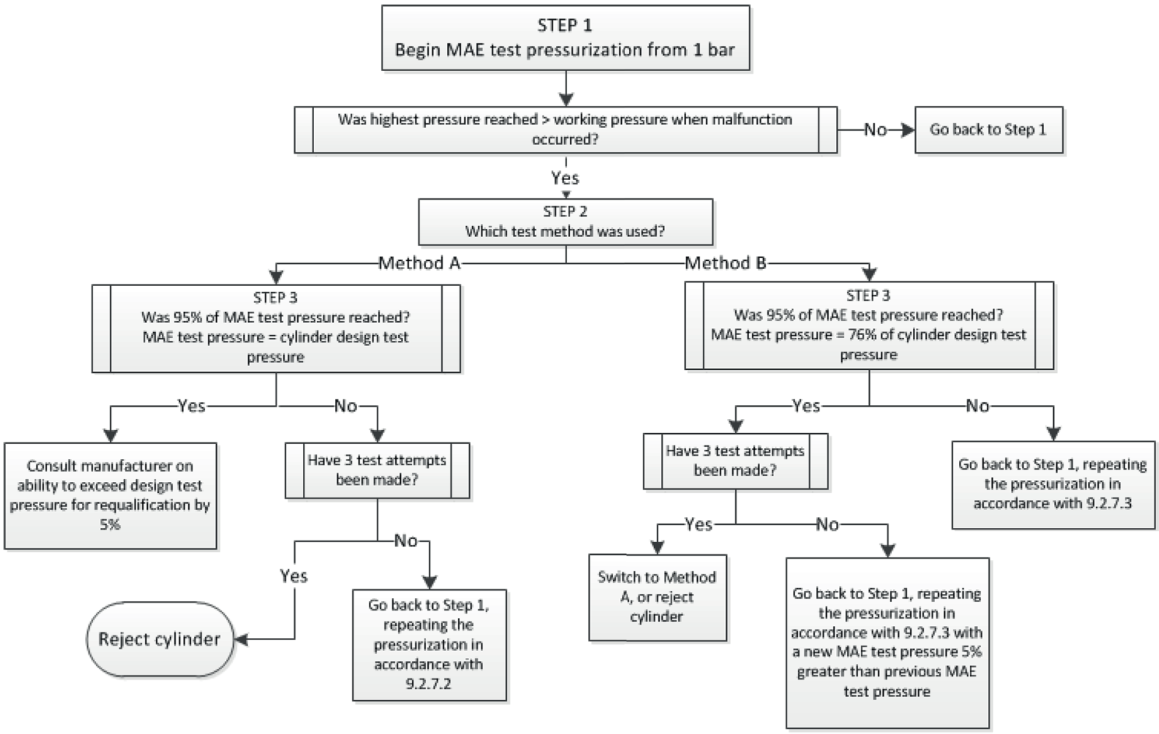


Figure 3 — Decision tree to determine MAE repeat tests permissibility and execution

10 Interpretation

10.1 General

During MAE testing, all waveforms (events) above the set threshold (see 9.2.5) are recorded. The MAE system distinguishes between extraneous noises (e.g. mechanical rubbing) and valid emissions (e.g. fibre breakage, delamination).

10.2 Noise filtering

10.2.1 General

Prior to the evaluation of the rejection criteria, any secondary AE [electromagnetic interference (EMI), mechanical rubbing, flow noise, etc.] shall be filtered out so that only the primary AE is analysed. Identify noise events by their shape, spectral characteristics or other information known about the test such as a temporally associated disturbance due to the pressurization system or test fixture as described in 10.2.2 through 10.2.6.

10.2.2 Electromagnetic interference (EMI)

EMI is characterized by a lack of any mechanical wave propagation characteristics, particularly an apparent lack of dispersion. EMI can be further identified by simultaneous signal arrivals on more than one channel. The two criteria shall be considered together to ensure it is not an event centred between the sensors.

10.2.3 Mechanical rubbing

Mechanical rubbing produces frequencies that are usually very low and should be identified and controlled.

10.2.4 Flow noise

The pressurization rate shall be such that flow noise does not interfere with the MAE test. Flow noise is characterized by waves that fill the waveform window.

10.2.5 Leakage

Leaks from a cylinder or its fittings can compromise the data as the leaks can produce acoustic signals. Leak noise is characterized by waves that look uniform across the entire length of the waveform window.

If a leak occurs in a fitting during the MAE test, the internal pressure of the cylinder shall be reduced to atmospheric pressure, the fitting repaired and the MAE test repeated in accordance with 9.2.9. If a leak occurs in the cylinder, the cylinder shall be rejected in accordance with Clause 13.

10.2.6 Clean front end

Use only events which have clean front ends and in which the first arrival channel can be determined.

10.3 Data analysis

MAE data to be analysed includes matrix splits, matrix cracks, fibre breaks and interfacial failure mechanisms due to fracture surface fretting and fibre/matrix debonding.

Extraneous noise (flow noise, mechanical rubbing, etc.), which is identified by waveform characteristics, may be included in the data. However, these extraneous noises shall be removed prior to performing the final MAE data analysis.

11 Evaluation and rejection criteria

11.1 Evaluation

Cylinders that experience fibre tow failure as defined in 11.2.3 and 11.2.4 shall be rejected and removed from service in accordance with Clause 13.

Events that occur at higher loads (i.e. greater than the cylinder's working pressure) during pressurization that have significant energy and frequency content in the applicable frequency bands (as defined in Criteria 1, 2 and 3 in Annex A) are typically due to single fibre, partial fibre tow or complete fibre tow breaks. These events should not be present at pressures up to normal operating pressure (working pressure) in cylinders that have previously experienced much greater pressures.

11.2 Analysis procedure

11.2.1 General

The following criteria shall be applied to the waveforms recorded during the MAE test pressurization and MAE test pressure hold. If Method A was selected, the rejection criteria from 11.2.2 and 11.2.3 should only be applied to waveforms captured at test pressure.

If any of the following criteria are met, the cylinder shall be rejected.

11.2.2 Rejection due to partial fibre bundle rupture criteria

Criteria 1, 2 and 3 in Annex A shall be applied to determine if fibre bundle breakage has occurred during the MAE test. If all the criteria in Annex A have been met, the fibre bundle rupture rejection criteria have been met. When the distance-attenuation-normalized energy for a validated source location of a single fibre bundle rupture event on any channel exceeds $U_{\text{FBB}}^{\text{AE}}$, rejectable fibre bundle rupture damage has occurred during the MAE test. See Formula (3).

$$U_{\text{FBB}}^{\text{AE}} = F_1 \times U_{\text{FB}}^{\text{AE}} \tag{3}$$

To establish allowance factors, physical testing on cylinders of nominal design that have experienced representative service need to be subjected to compromising situations (impact, notch tolerance, etc.) to identify cylinders that exhibit performance degradation which results in compromising the minimum design burst pressure. See Tables B.1, B.2 and B.3 for representative values of allowance factors.

In the absence of physical testing or stress calculation that demonstrates a relevant allowance factor, a conservative value of $F_1 = 100$, which is equivalent to stating that 100 average strength fibres ruptured in a tow (partial bundle rupture), shall be used.

11.2.3 Rejection due to single event energy

If the energy of a single event on any channel exceeds $F_2 \times U_{\text{FB}}^{\text{AE}}$, the cylinder shall be rejected. See Annex A for calculating the value $U_{\text{FB}}^{\text{AE}}$. When the distance-attenuation-normalized energy for a validated source location of a single event energy on any channel exceeds $F_2 \times U_{\text{FB}}^{\text{AE}}$, rejectable single event energy damage has occurred during the MAE test.

To establish allowance factors, physical testing on cylinders of nominal design that have experienced representative service need to be subjected to compromising situations (impact, notch tolerance, etc.) to identify cylinders that exhibit performance degradation which results in compromising the minimum design burst pressure. See Tables B.1, B.2 and B.3 for representative values of allowance factors.

In the absence of testing or calculation of a relevant allowance factor, a conservative value of $F_2 = 10\,000$ shall be used.

11.2.4 Rejection due to background energy (BE) and background energy oscillation (BEO)

The cylinder shall be rejected if the background energy (BE) moving average increases and exceeds $U_{\text{BE}} \geq M_1\ (U_{\text{QE}})$, where U_{QE} is the quiescent BE. A value of $M_1 = 2$ shall be used unless test data or calculation demonstrates that a larger (less conservative) value is appropriate to the type of material and vessel under inspection. If oscillations in the BE greater than M_2 (difference between the maxima and minima values of BE from neighbouring cycles) occur at any time during the test, the vessel shall be depressurized immediately and the cylinder rejected. A value of $M_2 = 2$ shall be used unless test data or calculation demonstrates that a larger (less conservative) value is appropriate to the type of material and vessel under inspection.

To establish allowance factors, physical testing on cylinders of nominal design need to be subjected to compromising situations (impact, notch tolerance, etc.) to identify cylinders that exhibit performance degradation which results in compromising the minimum design burst pressure. See Tables B.1, B.2 and B.3 for representative values of allowance factors.

12 Test report

A report shall be generated for each cylinder examined by MAE. The test report applies to both Method A and Method B and shall include the following information:

— cylinder design specification;

— name(s) of owner(s) of cylinders;

— MAE technician's name and certification level;

— serial numbers and manufacturer name(s) of cylinders;

— MAE test method used (A or B);

— MAE test pressure;

— sensor configuration;

— attenuation data derived from 9.2.4;

— pressurization medium;

— cylinder design test pressure (cylinder marked test pressure);

— cylinder water capacity;

— event energies exceeding the fibre bundle fracture criteria described in 11.2.2 (accept/reject);

— event energies exceeding the single event energy criteria described in 11.2.3 (accept/reject);

— allowance factor values (F_1, F_2, M_1, and M_2);

— BE rise, if applicable (accept/reject);

— BEO pressure, if applicable (accept/reject);

— date of MAE test and facility where test was performed;

— visual inspection results (accept/reject); and

— previous examination date and previous test pressure.

13 Rejection and rendering cylinders unserviceable

The decision to reject a cylinder may be taken at any stage during the periodic inspection and testing procedure. If it is not possible to recover a rejected cylinder, the testing facility shall, at the discretion of the owner, condemn the cylinder by rendering it unserviceable for holding gas under pressure so that it cannot be reissued into service.

One of the following methods shall be used to render the cylinder unserviceable:

— crushing the cylinder using mechanical means;

— cutting the neck off the cylinder; or

— cutting the cylinder in two or more irregular pieces.

Annex A
(normative)

MAE testing equipment specification

A.1 General

The MAE system shall have adjustable memory depth (wave window length) and adjustable sampling rate for the high-speed A/D converter. They shall be set accordingly for the MAE test requirements as follows.

The memory depth (wave window length) and sampling speed are dictated by the test requirements and calculated as shown in Formulae (A.1) and (A.2). Use C_E = 5 080 m/s and C_F = 1 270 m/s as a guide. The actual dispersion curves for the material shall be used if available.

$$L/C_E = t_1 \quad \text{(A.1)}$$

$$L/C_F = t_2 \quad \text{(A.2)}$$

Formula (A.3) is the minimum waveform window time and allows for pre-trigger time:

$$(t_2 - t_1) \times 1{,}5 \quad \text{(A.3)}$$

The sampling rate, or sampling speed, shall be such that aliasing does not occur.

The recording shall be quiescent before the front end of the E wave arrives. This is called a clean front end (see 10.2.6).

In order to determine if fibre bundle breakage has occurred during the MAE test, the frequency spectra of the direct E and F waves shall be analysed by software that performs such analysis and the energies in certain frequency ranges as given below shall be computed.

U ranges are defined as:

	kHz
U_0	50–400
U_1	100–200
U_2	250–400

The energies in the different ranges are compared as follows to determine if fibre breaks have occurred during the test:

Criterion 1: $U_0 \geq U_{FBB}^{AE}$, the energy in the waveform shall be greater than or equal to the fibre bundle breakage energy.

Criterion 2: $\frac{U_2}{(U_1 + U_2)} \geq 15\,\%$, the waveform energy contained in the higher frequencies is greater than or equal to the energy in the intermediate frequency range.

Criterion 3: $\frac{U_2}{U_0} \geq 10\,\%$, which means the energy contained in the higher frequencies is not too small compared with the energy of the whole waveform. This distinguishes delamination and matrix cracking waveforms from fibre rupture waveforms.

In the above, U_{FB} is calculated using the average breaking strength found in literature, from the manufacturer's data or independent test data. Formula (A.4) shall be used for calculating the average single fibre break energy:

$$U_{FB} = \frac{E\varepsilon^2}{2} \times \frac{\pi d^2}{4} \times l \tag{A.4}$$

If the ineffective fibre length is not readily available, four times the fibre diameter shall be used.

U_{FB} is calculated and subsequently scaled by the rolling ball impact energy conversion to determine U_{FB}^{AE} as shown in Formula (A.5):

$$U_{FB}^{AE} = U_{FB}\left[\frac{U_{RBI}^{AE}}{U_{mgh}}\right] \tag{A.5}$$

See Annex B for an example calculation using Formula (A.4).

A.2 Total single event energy

Friction between fracture surfaces plays a very important role in understanding MAE in cylinders that have delamination growth within their microstructure. It is an indicator of the presence of damage because it is produced by the frictional rubbing between existing or newly created fracture surfaces. Even the presence of fibre bundle breakage can be detected by examining the waveforms produced by frictional acoustic emission (FRAE). Increasing FRAE intensity throughout a pressure cycle indicates increasing damage. FRAE energies can be quite large. An allowance factor (F_2) shall be determined through testing of similar cylinders and input into the software used for the MAE analysis of the rejection criteria.

A.3 BE and BEO

During pressurization, the BE of any channel might begin to rise and, at some point, begin to oscillate (BEO). The multiplicative factor (M_1) for the quiescent BE rise and the BEO multiplicative factor (M_2) can be different for different materials and composite cylinder type, size and pressure rating. The values of M_1 and M_2 can be determined by performing MAE testing to burst on a statistically representative sample of composite cylinders.

Annex B
(informative)

Overview of modal acoustic emission (MAE) test method

B.1 General

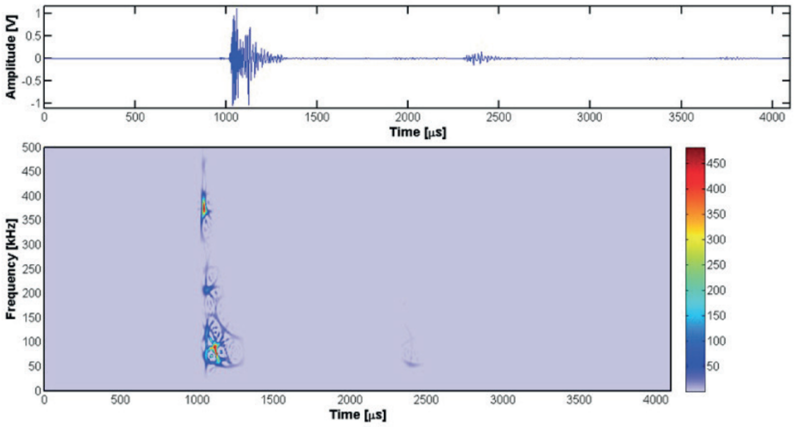
Composite fracture mechanisms are numerous but consist primarily of matrix cracking, delamination between layers, fibre breakage, fibre to matrix debonding and fibre pull-out. Acoustic emission modes are created by all of these mechanisms as well as by another very important source, friction between newly created fracture surfaces. Experience shows that composite overwrapped pressure cylinder failure is controlled by fibre fracture.

The main purpose of monitoring MAE in these cylinders is for the determination of fibre breakage, since it is fibre breakage that primarily controls cylinder strength. It should be noted that it is unlikely that significant fibre breakage will occur at operating pressure unless damage is present. That is why any sign of fibre events is considered particularly significant and there are specific evaluation criteria given herein for fibre breakage events.

An AE event is a mechanical impulse that generates a wave that propagates in all directions from the source. Such impulses are created by the composite fracture mechanisms and can be modelled using elastodynamic theory. As the impulse propagates through the material, it changes shape due to wave propagation considerations, dispersion and attenuation. The mechanical impulse is detected by one or more sensors coupled to the material at some distance from the source. The detected signal, or waveform, is captured and analysed. Since there are multiple fracture mechanisms, the waveform produced by a given fracture mechanism shall be distinguished from all others if the fracture mechanism is to be uniquely identified.

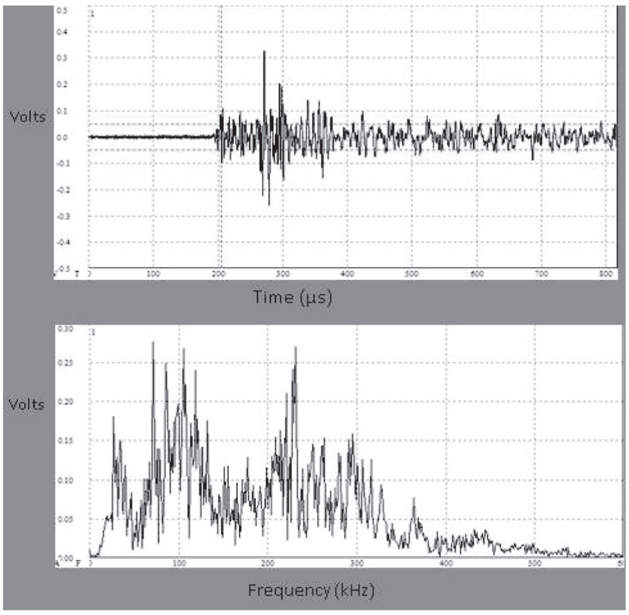
A captured AT waveform is distinguished by the wave (mode) shapes, the wave (mode) energies and the wave (mode) frequency spectrum. These quantities are then related to elastodynamic theory. Stress and strain analysis, fracture mechanics and testing of composite materials provide additional insight into how to use the elastodynamic modelling. Using these methods, the waves are analysed to determine whether the source is a delamination event, a matrix crack event, a fibre bundle breakage event or a frictional event.

Figures B.1 and B.2 demonstrate detection and confirmation of fibre breakage. Figure B.3 is an example of BE and BEO.



NOTE Frequency content above 300 kHz along with spectral shape are used to confirm fibre rupture.

Figure B.1 — Example of MAE waveforms for fibre bundle breakage



NOTE The waveform shape and spectrum is different from the fibre fracture event shown in Figure B.1.

Figure B.2 — Matrix crack waveform

B.2 Examples of fibre break energy calculation

For a typical carbon fibre with the following specifications, U_{FB} can be calculated by substituting these values into Formula (A.4):

d = 7 µm,

E = 200 GPa,

ε = 0,01 (average breaking strain) for some carbon fibre, and

l = 4d.

$U_{FB} = 1{,}077 \times 10^{-8}$ J

For a representative glass fibre with the following specifications, U_{FB} can be calculated by substituting these values into Formula (A.4):

$d = 13$ µm,

$E = 70$ GPa,

$\varepsilon = 0{,}04$ (average breaking strain) for some glass fibre, and

$l = 4$d.

$U_{FB} = 3{,}87 \times 10^{-7}$ J

B.3 Example of energy scaling calculation

Assume that the $U^{AE}{}_{RBI}$, measured by a particular high-fidelity AT sensor, is 5×10^{-10} J and U_{RBI} is $1{,}9 \times 10^{-3}$ J (due to gravitational potential energy). The U_{FB} of the example carbon fibre is $1{,}077 \times 10^{-8}$ J, which would correspond to a wave energy as per Formula (B.1):

$$U_{FB}^{AE} = U_{FB}\left[\frac{U_{RBI}^{AE}}{U_{RBI}}\right] \tag{B.1}$$

$= 1{,}077 \times 10^{-8}$ J $\times 5 \times 10^{-10}$ J$/1{,}9 \times 10^{-3}$ J

$= 2{,}83 \times 10^{-15}$ J

This number is used to calculate the value of U_{FB}^{AE}, which is subsequently used in the fibre bundle breakage accept/reject criterion and the single event energy accept/reject criterion.

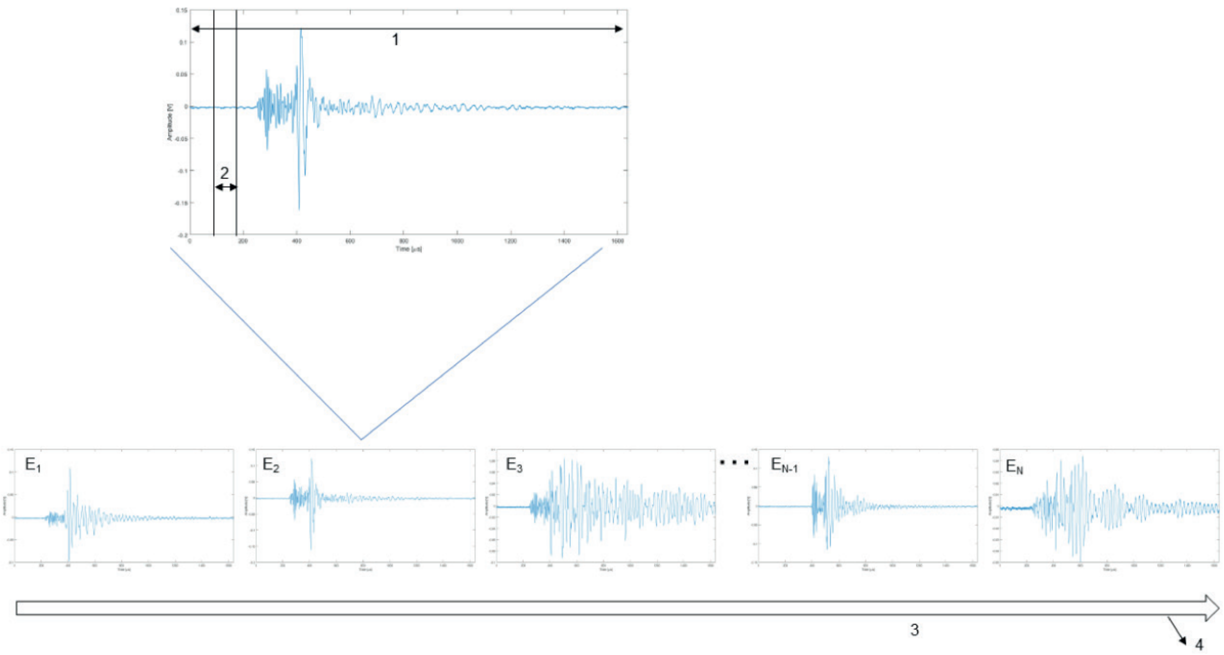
Table B.1 provides representative allowance factors (F_1) for various cylinder specifications.

Table B.1 — Representative examples of F_1 by cylinder type

Design type	Diameter (mm)	Fibre type	Test pressure (bar)	Stress ratio	F_1 [a]
III	178	High-strength carbon	517	2,04	12 000
IV	305	S-glass	40,5	2,0	3 000
IV	1 066	High-strength carbon	372	1,5	24 000
IV	406	High-strength carbon	1 050	1,5	24 000

[a] These representative values should be verified through testing (e.g. impact and burst) for given cylinder specifications.

B.4 Processing of waveforms, BEs and BEOs



Key

1 wave window length

2 BE window length

3 form running average of BEs

4 test running average for rejectable oscillations

Figure B.3 — Demonstration of steps of BE and BE oscillations

B.5 Allowance factor or single event energy

The allowance factor for a single event energy is the maximum energy allowed for any waveform. These waves are produced by delamination, outer layer debonding and frictional emission. High energy frictional emission is important because it reveals extensive existing damage that could have been caused, for example, if the cylinder was subjected to a severe impact. Cylinders are designed to sustain such events and not fail before the next pressure test interval, but they should be removed from service at the earliest opportunity. It should be noted that hydrotesting without MAE typically does not reveal such damage. Subjecting a few similar cylinders to ISO 11119-2 cut and impact testing should be carried out to confirm the allowance factor appropriate to that type of cylinder.

Table B.2 provides representative allowance factors (F_2) for various cylinder specifications.

Table B.2 — Representative examples of F_2 by cylinder type

Design type	Diameter (mm)	Fibre type	Test pressure (bar)	Stress ratio	F_2[a]
III	178	High-strength carbon	517	2,04	1 200 000
IV	305	S-glass	40,5	2,0	300 000
IV	1 066	High-strength carbon	372	1,5	2 400 000
IV	406	High strength carbon	1 050	1,5	2 400 000

[a] These representative values should be verified through testing (e.g. impact and burst) for given cylinder specifications.

B.6 BE and BEO

BE is an important indicator of ongoing damage and a precursor to new severe damage because it is caused by rapid and successive matrix cracking and fibre failures that occur in a weak area or near a stress concentration. BE is actually a series of small acoustical impulses that occur close together in time and give the appearance of continuous emission. When examined closely, individual events can be distinguished including fibre breaks, matrix cracking and FRAE. In an undamaged cylinder, BE decreases significantly during a load hold and depressurization because the driving force behind the small events is removed.

The BE for a given waveform is measured by calculating the minimum energy value in a contiguous windowed portion of the waveform. Typically, the minimum energy window will occur in the pre-trigger portion of the waveform, but this is not always the case. To determine if BEOs are occurring, an N point moving average of the BE values is calculated and the differences in neighbouring maxima and minima are determined.

Further, a rise in the BE moving average is compared with the quiescent BE. The quiescent BE is measured by exciting a wave using a pencil lead break on the vessel, or transmitting some other known type of pulse, prior to commencing the filling operation. The received waveform should have a clean front end.

During a pressurization test, an indication that the cylinder might be damaged in that section of material is if the BE at one sensor rises compared with the quiescent BE. Matrix and fibre failures are occurring within that section as load transfer progresses over an increasing region of the material. Load transfer continues until a strong region is encountered and the progression of the damage is interrupted. However, if the load is increased further, the scenario can repeat and a failure can happen. This failure can be predicted by oscillations in the BE.

BEO has been correlated with burst pressure. A cylinder shall be removed from service and rendered unserviceable in accordance with Clause 13 when it no longer has the required burst safety factor.

Table B.3 provides representative allowance factors (M_1 and M_2) for various cylinder specifications.

Table B.3 — Representative examples of M_1 *and* M_2 by cylinder type

Design type	Diameter (mm)	Fibre type	Test pressure (bar)	Stress ratio	M_1[a]	M_2[a]
III	178	High-strength carbon	517	2,04	2	2
IV	305	S-glass	40,5	2,0	6	6
IV	1 066	High-strength carbon	372	1,5	4	4
IV	406	High-strength carbon	1 050	1,5	4	4

[a] These representative values should be verified through testing (e.g. impact and burst) for given cylinder specifications.

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