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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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Foreword

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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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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 $0{,}01 \times 10^{-15}$ 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 $Temp_{\max}$

Note 1 to entry: $Temp_{\max}$ 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
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

F_2
allowance factor for single event energy

3.1.25

BE multiplication factor
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
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
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).

